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by

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16. ABSTRACT

The National Acid Precipitation Assessment Program created the Forest Response Program(FRP) to assess the effects of acidic deposition on trees and forests in regions of the United States. Research from the FRP and other programs is summarized in four Major Program Output documents that address policy questions regarding forest condition, mechanisms of effects of air pollutants, and projected responses of pollutants on forests. This document summarizes information available up to February, 1990.

The major findings include several observations on mechanisms of effect. There is evidence that supports the hypothesis that acidic deposition alters soil chemical properties. The rate of changes in soil chemical properties and how trees may respond to the changes is not certain. Controlled exposures of simulated acid precipitation most often showed no effect on growth of seedlings, but caused delayed development of cold tolerance in red spruce seedlings. Ozone caused decreased growth in most seedlings tested, but at levels higher than typical ambient ozone concentrations. Species that may be sensitive to ozone at ambient levels include ponderosa pine and loblolly pine. The findings allow conclusions regarding consistency between forest condition and pollutant levels in several regions of the United States.

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The findings allow conclusions regarding consistency between forest condition and pollutant levels in several regions of the United States. Observations of foliar injury symptomatic of ozone exposure on ponderosa pine and Jeffrey pine in the San Bernardino Mountains and in the Sierra Nevada of California are spatially and temporally consistent with measured increases in average ozone concentrations. The number of standing dead red spruce in the Adirondack and Green Mountains of the northern Appalachians increases with elevation. At elevations above cloud base (800-1200 m), atmospheric deposition of acids and acidifying substances is estimated to be twice that below cloud base. There is consistency between soil chemical properties or nutrient cycling properties and spatial trends of atmospheric deposition of sulfate and associated ions in the eastern hardwoods region. However, change in forest condition associated with the atmospheric deposition patterns in the eastern hardwoods is not pronounced. Some reduction in radial growth of oak has been observed on sites with low soil calcium-to-aluminum ratios. Although decreased radial growth of loblolly pine in natural stands growing in the Piedmont region of the South has been observed in recent years compared with earlier years, consistency with ozone levels cannot be established since exposures of these stands to ozone has not been quantified. The decrease in radial growth in the stands of loblolly pine is also related to recent increases in stem density and increased age of the trees.

NOTICE

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TABLE OF CONTENTS

1 EXECUTIVE SUMMARY 1

  1.1 Policy Question #1 1

    1.1.1 Acidic Deposition 1

    1.1.2 Ozone 2

  1.2 Policy Question #2 2

    1.2.1 Soils 2

    1.2.2 Roots and Mycorrhizae 3

    1.2.3 Carbon Allocation 3

    1.2.4 Winter Injury 3

    1.2.5 Foliar Leaching 3

  1.3 Conclusion 3

2 INTRODUCTION 5

  2.1 Forest Response Program 5

  2.2 Purpose of this Document 8

  2.3 Background and Statement of the Problem 8

  2.4 FRP Research Methods 9

  2.5 Summary of MPO #1&2 9

    2.5.1 Changes in Forest Condition 10

    2.5.2 Spatial Patterns in Forest Condition and Pollutant Exposure 10

  2.6 Summary of MPO #3 10

    2.6.1 Effects of Sulfur Dioxide 10

    2.6.2 Effects of Acidic Deposition 10

    2.6.3 Effects of Ozone 11

  2.7 Summary of Atmospheric Deposition and Pollutant Exposure 11

  2.8 Ozone Exposure 16

3 RESULTS AND DISCUSSION 21

  3.1 Soil Chemistry and Nutrient Cycling 22

    3.1.1 Trends Along Regional Deposition Gradients 22

    3.1.2 Trends Along Elevational Gradients of Cloud Deposition 28

    3.1.3 Experimental Additions of Acidic Solutions to Soils 31

    3.1.4 Literature Reviews and Modeling Projections 34

    3.1.5 Tree Condition as a Function of Soil Chemistry 34

    3.1.6 Soil Studies of Other Programs 35

    3.1.7 Summary 41

  3.2 Roots and Mycorrhizae 42

    3.2.1 FRP Seedling Studies 42

    3.2.2 FRP Mature Tree Studies 43

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3.2.3 NCASI Results 43
3.2.4 ROPIS Results 43
3.2.5 Summary 44
3.3 Altered Carbon Allocation 44
3.3.1 FRP Seedling Studies 44
3.3.2 FRP Mature Tree and Sapling Field Studies 48
3.3.3 FRP Branch Exposure Studies 49
3.3.4 ROPIS Results 51
3.3.5 Summary 54
3.4 Winter Injury 54
3.4.1 FRP Seedling Studies 54
3.4.2 FRP Mature Tree and Sapling Field Studies 56
3.4.3 ROPIS Results 56
3.4.4 Summary 58
3.5 Foliar Leaching 58
3.5.1 FRP Seedling Studies 58
3.5.2 FRP Mature Tree and Sapling Field Studies 58
3.5.3 IFS Results 59
3.5.4 ROPIS Results 59
3.5.5 Summary 59
3.6 Insects and Pathogens 59
3.7 Reproduction and Regeneration 62
3.8 Forest Condition Studies 63
3.8.1 Western Conifers 63
3.8.2 Spruce-Fir 63
3.8.3 Southern Commercial Pines 65
3.8.4 Eastern Hardwoods 65
3.8.5 Summary 66
4 SUMMARY AND CONCLUSIONS 67
4.1 Purpose of this Document 67
4.2 Summary of Principal Findings 67
4.2.1 Soils 67
4.2.2 Roots and Mycorrhizae 68
4.2.3 Carbon Allocation 68
4.2.4 Winter Injury 68
4.2.5 Foliar Leaching 69
4.2.6 Forest Condition 69
4.3 Answers to Policy Questions 70
4.3.1 Acidic Deposition 70

4.3.2 Ozone 71
4.4 Recommendations for Future Research 71
4.4.1 Soils 71
4.4.2 Roots 72
4.4.3 Carbon Allocation 72
4.4.4 Winter Injury 72
4.4.5 Foliar Leaching 72
4.4.6 Forest Condition 72
4.4.7 Atmospheric Deposition 73
4.4.8 Controlled Exposure Studies 73
5 ACKNOWLEDGMENTS 74
6 LITERATURE CITED 75
7 APPENDICES 90
7.1 Appendix A: Assessment of Data Quality 90
7.1.1 Use of Data Quality Assessments 90
7.1.2 Quality Assurance Activities 90
7.1.3 Quality Assurance Findings 91
7.1.4 Quality Assurance of Branch Exposure Chambers 92
7.2 Appendix B: Methods and Materials 97
7.2.1 Forest Condition Surveys 97
7.2.2 Atmospheric Deposition Data 99
7.2.3 Controlled Exposure Studies 100
7.3 Appendix C: Abbreviations 103
7.4 Appendix D: Scientific Names of Trees 104
7.5 Appendix E: Summary Tables of FRP Research 105

1 EXECUTIVE SUMMARY

The Forest Response Program (FRP) is a cooperative research program of the US Environmental Protection Agency, the USDA Forest Service, and the National Council of the Paper Industry for Air and Stream Improvement, Inc., initiated under the National Acid Precipitation Assessment Program. The purpose of the FRP is to determine the nature and extent of the effects of acidic deposition and associated pollutants on trees and forests in regions of the United States. This document is one of a series of Major Program Outputs (MPOs) that summarizes research from the FRP and other programs and that addresses questions relevant to environmental policy.

The purpose of this document (MPO #4) is to address two policy questions posed at the initiation of the FRP:

1. Is there significant forest damage in North America caused by acidic deposition, alone or in combination with other pollutants?
2. By what mechanisms does acidic deposition, alone or in combination with other pollutants, contribute to forest damage in North America?

1.1 Policy Question #1

In this section, we summarize research on forest condition to evaluate whether there is significant forest damage in North America that may have been caused by acidic deposition. Because ozone is the most widespread phytotoxic air pollutant found in forested regions, we also summarize research designed to determine how ozone may be affecting forest condition.

1.1.1 Acidic Deposition

Significant forest damage (change greater than expected) is thought to be occurring among red spruce at high elevations in the Appalachian Mountains of the northeastern United States based on three observations of forest condition: 1) high proportions of standing dead red spruce basal area above 1000 m in the Adirondack and Green Mountains; 2) reductions in radial growth of red spruce in many areas; and 3) tree condition visually assessed to be poor or declining over time. The range of possible natural variation in forest condition is quite large. The observed changes in red spruce at high elevations may not be outside the range of natural variability, but it does appear that they are above normal expectation and are consistent with increasing levels of wet deposition. In addition, experiments with red spruce have linked acidic mists to decreased cold tolerance in seedlings and ambient cloud water to increased winter injury to mature branches. Winter injury has been associated with reduced red spruce growth in a field provenance study. These experimental and field observations are consistent with the hypothesis that repeated winter injury, exacerbated by high levels of acidic cloud water deposition, may contribute to reduced radial growth and deteriorated crown condition in red spruce. To date, however, no experimental evidence has demonstrated conclusively that acidic deposition is a direct cause of increased mortality of red spruce.

Significant forest damage has not been detected in the eastern hardwoods. No relationship has been established between biomass increment and spatial patterns of sulfate deposition in Michigan. However, reduced radial growth has been observed in black and white oaks on sites with low soil calcium-to-aluminum ratios (0.25 molar ratio in the upper 50 cm of soil) in the Ohio River Valley.

1.1.2 Ozone

Ozone has been shown to cause foliar injury, decreased growth, and increased mortality of sensitive individuals of specific forest tree species. Ozone has caused foliar injury to sensitive individuals of white pine over much of its range in eastern North America. Ozone has also resulted in reduced growth of sensitive white pines in the Blue Ridge Mountains of Virginia and in a plantation in eastern Tennessee. In addition, ozone has caused foliar injury, reduced needle retention, decreased photosynthesis, and reduced growth eventually leading to increased mortality (caused by the western pine beetle) of ponderosa pine and Jeffrey pine in the San Bernardino Mountains in southern California. There is spatial consistency between ozone exposure and symptomatic crown injury to mature ponderosa pine along a 500-km north-to-south corridor in the southern Sierra Nevada. Ozone occurs in concentrations sufficient to cause visible injury to vegetation in most of eastern North America.

Ozone may be causing growth reductions in southern pines, although no data directly demonstrate this. Three observations support this conjecture: 1) in selected instances, loblolly pine seedlings and mature branches of loblolly pine show reductions in photosynthesis at ambient ozone levels (i.e., 40-50 ppb); 2) a reduction in radial growth of loblolly pine has been observed in natural stands in the Piedmont; and 3) potentially phytotoxic levels of ozone have been measured in this region (43-51 ppb). However, other information limits this conjecture. A number of the seedling studies did not show reductions in photosynthesis at ozone levels twice ambient. The reductions in growth in loblolly pine stands may be due to natural factors, since stand density changes and increased competition from hardwoods have not been accounted for in these surveys. Until these uncertainties are resolved, ozone-induced growth declines of loblolly pine in the South cannot be established.

1.2 Policy Question #2

Scientific questions were posed at the beginning of the FRP to address Policy Question #2; that is, to determine mechanisms for forest damage due to acidic deposition. Possible mechanisms for forest damage identified in these scientific questions include changes in soil chemistry/effects on roots and mycorrhizae, altered carbon allocation, winter injury, foliar leaching, insects and pathogens, and altered reproduction and regeneration. Research projects designed to answer the scientific questions included surveys of forest condition, dendroecological studies, characterization of pollutant deposition, controlled exposures of seedlings and branches of mature trees to pollutants, soil studies, and forest ecological studies along deposition gradients. The answers to the scientific questions based on the research presented in this document can be summarized as follows.

1.2.1 Soils

Several observations support the hypothesis that atmospheric deposition of acidic or acidifying substances such as hydrogen, sulfate, nitrate, and ammonium ions alters soil chemical properties. Changes in soil chemistry similar to those that would be expected as a result of soil acidification were observed along four regional gradients of increasing sulfate deposition in eastern hardwood forests. When compared with lower elevations on Mt. Moosilauke, NH, and Whiteface Mountain, NY, changes in soil chemistry under red spruce were observed at high-elevation sites where deposition of sulfate is high due to high cloud water deposition. Two analyses of the extent of susceptible soils and acidic deposition in the Southeast indicated that loss of soil cations and increases of soil nitrogen will occur in some soils. The timing of this change is uncertain. Soil chemical changes induced by artificial additions of acid were consistent with trends observed in the field.

1.2.2 Roots and Mycorrhizae

Responses of seedling root growth to simulated acid precipitation were highly variable. No consistent effects of acidity on growth or mortality of roots were evident in these studies.

Root growth of loblolly pine, trembling aspen, Douglas-fir, ponderosa pine, and lodgepole pine seedlings was reduced by ozone. A possible mechanism appears to be reduced carbon allocation to roots. Mycorrhizal frequency may be reduced and morphotype distributions may be altered by ozone; however, this work is still preliminary.

1.2.3 Carbon Allocation

In seedling studies, tested levels of acidity ranged from pH 2.1 to 5.6, with typical values from pH 3.0 to 5.0. Compared with control treatments (i.e., the highest pH value used), over half the studies showed no effects of increased acidity on foliage biomass, stem growth, or root growth. The remaining studies showed both increased growth and decreased growth. Increased photosynthesis of seedlings in treatments with increased acidity of simulated acidic precipitation was observed in some studies of red spruce and southern pines.

Ozone exposures of seedlings ranged from charcoal-filtered air to 320 ppb, with typical values ranging from charcoal-filtered to 3-times-ambient concentrations, or about 120 ppb (ambient site concentrations ranged from 33 to 48 ppb). Compared with control treatments (the lowest ozone level), ozone exposure led to decreased growth in most studies. Loblolly pine, ponderosa pine, western hemlock, and black cherry showed decreases in above- and/or belowground growth. In addition, loblolly pine also showed reduced photosynthesis. Photosynthesis was not measured for ponderosa pine, western hemlock, or most hardwood species.

1.2.4 Winter Injury

In controlled tests of simulated acidic precipitation, increasing acidity decreased the rate of development of cold tolerance of red spruce seedlings. The response was fairly linear as acidity increased, starting as high as pH 4.0. Solutions containing sulfuric acid caused greater injury following overnight freeze tests than solutions containing nitric acid. When cloud water containing ambient concentrations of pollutants was filtered from branch exposure chambers, freezing injury decreased for branches of mature red spruce in the field on Whiteface Mountain, NY. Reductions in radial growth, basal area increment, and height growth were associated with degree of over-winter injury to needles of 30-year-old red spruce trees growing in a provenance test site in northern New Hampshire.

1.2.5 Foliar Leaching

Precipitation acidity can increase foliar leaching, but the effects of canopy leaching on tree growth and health are unclear. In chamber exposures, most studies showed no effect of acidity on foliar nutrient levels. In the field, hydrogen ion loading and throughfall enrichment of cations were correlated in all of the reviewed studies, indicating a possible effect of precipitation acidity.

1.3 Conclusion

Damage to red spruce has been identified at high elevations in the northern Appalachians. At the highest elevations, acidic cloud water deposition and cold temperatures are greatest, and, in the Adirondack and Green Mountains, red spruce mortality and deteriorated crown condition is greatest. Three experimental findings support the hypothesis that reduced growth and crown deterioration of red spruce is related to winter injury, which may be increased by chronic deposition of acidic cloud water. First, controlled exposures of acidic precipitation caused reduced cold tolerance to current-year needles of red spruce seedlings during autumn hardening. Second, reduced exposure to ambient cloud water was associated with decreased winter injury to needles on branches of susceptible mature red spruce trees. Third, damage to needles in winter has been related to reduced carbon gain (shown as reduced height and diameter growth) in

30-year-old red spruce trees growing in a provenance study plot. Whether acidic cloud water can cause sufficient winter injury to lead to increased red spruce mortality is still to be determined.

Changes in forest condition (visible foliar injury or reduced growth) of some species sensitive to ozone have been identified in regions that may have relatively high ozone exposures. In particular, ponderosa pine in the San Bernardino Mountains and in the Sierra Nevadas of California have shown changes in forest condition. The condition of loblolly pine in natural (i.e., unmanaged) stands of the Piedmont may also have changed. However, the relationship between spatial and temporal distributions of ozone in the Piedmont and forest condition are as yet to be determined. Controlled exposures indicate that high levels of ozone cause reduced photosynthesis, reduced growth, reduced carbon allocation to roots, and increased foliage senescence in many species of seedlings, and ponderosa, Jeffrey, and loblolly pine appear to be particularly sensitive. Ozone has also been associated with reduced photosynthesis in mature loblolly pine. The effects of ozone on mature ponderosa pine are currently being studied using branch exposure chambers.

Soil chemical properties have been shown to change with controlled applications of acidic precipitation. Chemical properties of the soil and forest floor, such as exchangeable cations (notably calcium and magnesium), available aluminum, or sulfur contents, and nutrient cycling properties, such as nitrification, or chemistry of foliage and wood of trees, vary spatially in a manner consistent with patterns of acidic deposition. How such changes in soil chemical properties may be affecting trees in the forests is still under study. However, reduced growth of red spruce seedlings have been observed at soil solution aluminum (Al^{3+}) concentrations as low as 200 μM. These concentrations have been measured in association with high soil solution nitrate concentrations in red spruce stands at Whitetop Mountain, VA.

2 INTRODUCTION

The Forest Response Program (FRP) is a research initiative under Task Group V of the National Acid Precipitation Assessment Program (NAPAP). The FRP is responsible for estimating the actual and potential effects of acidic deposition and its associated pollutants on trees, forests, and forest ecosystems in regions of the United States (Schroeder and Kiester, 1989). This document reviews and summarizes research performed by the FRP and other programs.

2.1 Forest Response Program

The FRP is a joint program of the US Environmental Protection Agency (EPA), the USDA Forest Service (USFS), and the National Council of the Paper Industry for Air and Stream Improvement, Inc. (NCASI). The FRP was created in 1985 in an effort to consolidate into a national research program several separate programs that were collecting data on forests and acid rain. The objective of the FRP is to address three policy questions regarding the status of North American forests, the potential and actual effects of acidic deposition, mechanisms of the effects, and quantification of the effects.

The three policy questions are:

1. Is there significant forest damage in North America caused by acidic deposition, alone or in combination with other pollutants?
2. By what mechanisms does acidic deposition, alone or in combination with other pollutants, contribute to forest damage in North America?
3. What is the dose-response relationship between acidic deposition, alone or in combination with other pollutants, and forest damage in North America?

The FRP is organized into six research cooperatives with a national management structure. The six research cooperatives are responsible for managing research in identified problem areas. Four research cooperatives are organized according to forest regions. The Spruce-Fir (SF) Research Cooperative focuses primarily on red spruce and, to a lesser extent, balsam fir and Fraser fir in high-elevation spruce-fir forests of the Appalachian Mountains. The Southern Commercial (SC) Forest Research Cooperative studies commercially important pines of the southern states. The Eastern Hardwoods (EH) Research Cooperative examines hardwood species primarily in midwestern and northeastern states. The Western Conifers (WC) Research Cooperative studies conifer species in western states. The two remaining research cooperatives were organized to facilitate the collection and assembly of data sets: the National Vegetation Survey (VS) is concerned with inventories of forests conducted primarily through dendrochronology or surveys of permanent plots, and the Atmospheric Exposure (AE) Cooperative established pollutant deposition monitoring sites and developed cloud water collection techniques. The FRP also included two program-wide projects: Quality Assurance (QA), which is concerned with data integrity, and Synthesis and Integration (S&I), which provides technical support to the cooperatives and produces program-wide summaries such as this document.

At the beginning of the FRP, a series of scientific questions (Table 1) was formulated for each policy question to guide the research. As individual research projects progressed, the investigators' analyses of their data were made available to S&I. S&I was then responsible for producing documents called Major Program Outputs (MPOs) to answer the scientific and policy questions by synthesizing and integrating results across individual experiments where possible (see Table 2 for a list of these MPOs). The MPOs have two purposes: 1) to summarize FRP research for the scientific community; and 2) to answer the policy questions to the extent possible. The path from problem statement to research projects and MPOs is summarized in Figure 1.

Table 1. Original Scientific Questions of Policy Questions #1 and #2

Scientific Questions for Policy Question #1

1. Are changes in forest condition greater than can be attributed to natural variability?
2. What spatial patterns exist in forest condition and how do they relate to spatial patterns of pollutant exposure?

Scientific Questions for Policy Question #2

What are the effects of sulfur, nitrogen, and associated pollutants on forests through the mechanisms of:

1. a. direct toxicity to roots, mycorrhizae, or soil microbial populations by mobilized metal in acidified soil water;
    b. nitrogen toxicity to mycorrhizae; or
    c. increased leaching of soil nutrients resulting in reduced nutrient availability?
2. altered photosynthesis, respiration, and carbon allocation patterns (e.g., morphology) with possible induction of water and/or nutrient stress?
3. delayed cold hardening or premature break in dormancy resulting in increased winter

Table 2. Major Program Outputs, Associated Policy Questions, and Authors

MPO #1&2:	Extent and magnitude of recent changes in forest condition and the role of air pollution and non-air pollution factors. (Policy Question #1) (Reams et al., 1990)
MPO #3:	Seedling response to sulfur, nitrogen, and associated pollutants. (Policy Question #2)(Peterson et al., 1989)
MPO #4:	Response of forest trees to sulfur, nitrogen, and associated pollutants. (Policy Questions #1 and #2)(Mattson et al., 1990)
MPO #5:	Projection of responses of trees and forests to acidic deposition and associated pollutants. (Policy Question #3)(Kiester et al., 1989)

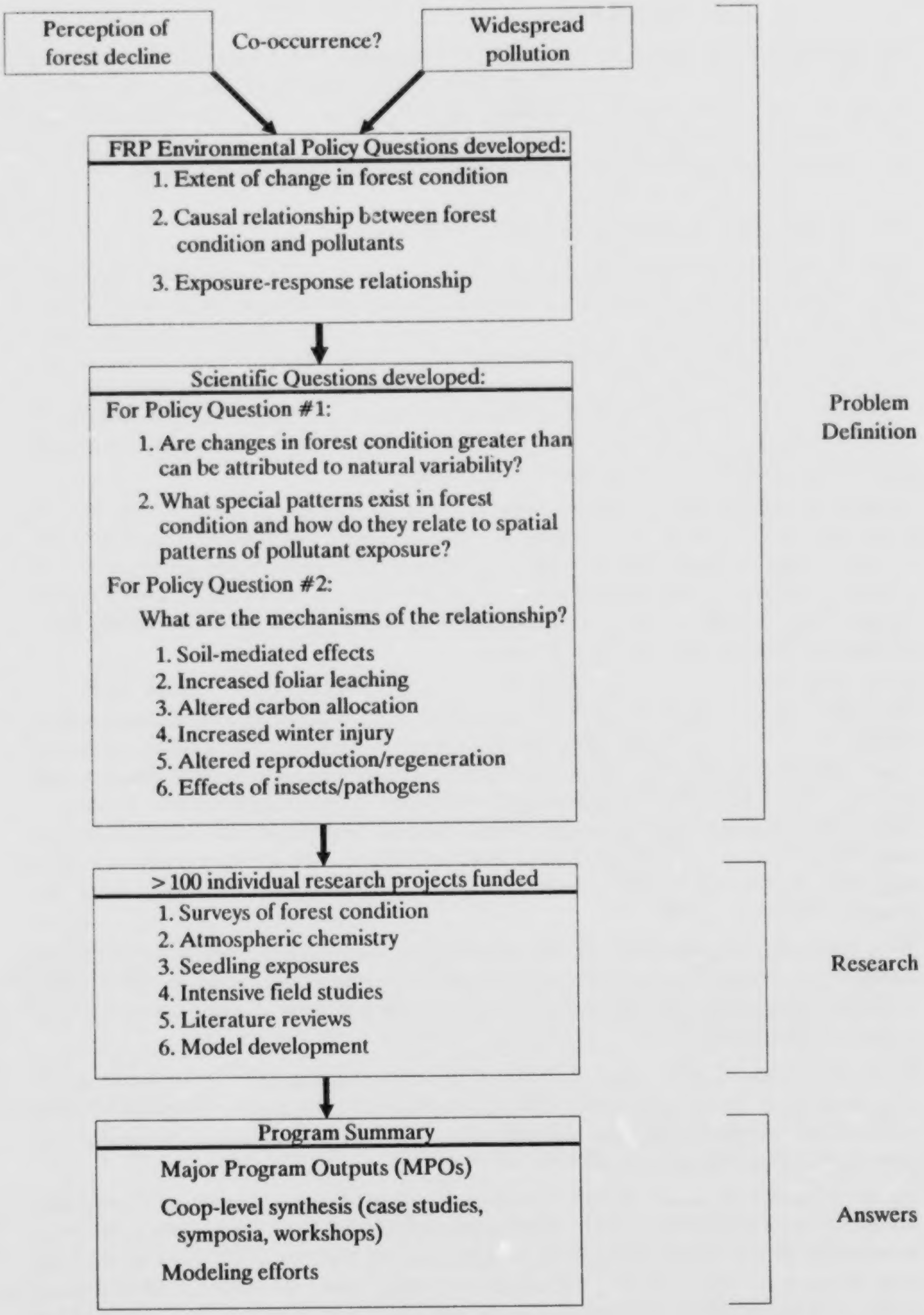
Perception of forest decline
Co-occurrence?
Widespread pollution
FRP Environmental Policy Questions developed:
1. Extent of change in forest condition
2. Causal relationship between forest condition and pollutants
3. Exposure-response relationship
Scientific Questions developed:
For Policy Question #1:
1. Are changes in forest condition greater than can be attributed to natural variability?
2. What special patterns exist in forest condition and how do they relate to spatial patterns of pollutant exposure?
For Policy Question #2:
What are the mechanisms of the relationship?
1. Soil-mediated effects
2. Increased foliar leaching
3. Altered carbon allocation
4. Increased winter injury
5. Altered reproduction/regeneration
6. Effects of insects/pathogens
> 100 individual research projects funded
1. Surveys of forest condition
2. Atmospheric chemistry
3. Seedling exposures
4. Intensive field studies
5. Literature reviews
6. Model development
Program Summary
Major Program Outputs (MPOs)
Coop-level synthesis (case studies, symposia, workshops)
Modeling efforts
Problem Definition
Research
Answers

Figure 1. The path from problem statement to research synthesis in the FRP.

2.2 Purpose of this Document

The purpose of this document (MPO #4) is, first, to summarize FRP research that was conducted to answer Scientific Questions 1 through 6 for Policy Question #2 and, second, to provide answers to Policy Questions #1 and #2. In meeting these objectives, we also review the findings of MPO #1&2 and MPO #3 since these documents incorporated many of the FRP studies discussed here and they attempted to answer aspects of Policy Questions #1 and #2.

2.3 Background and Statement of the Problem

Forest decline is defined as a response to one or more stresses, resulting in a decrease in the vigor of individuals of one or more tree species and often in increased mortality rates over a large area (Freedman, 1989; Weidensaul et al., 1989). Changes in forest condition can result from natural factors, such as stand dynamics, climate, insects, and pathogens, and from anthropogenic factors, such as harvesting, site preparation, and atmospheric deposition. These factors can act alone or in combination. In this section, we briefly review evidence from regions in Europe and North America that led to a perception of forest decline. For a more comprehensive historical perspective, see Brandt (1987) or Reams et al. (1990).

Concern over effects of air pollutants and acid rain dates back more than a century. In 1852, Smith described the chemical composition of rain and related increasing acidity in precipitation to industrial coal combustion (cited in Brandt, 1987). In 1871, Stöckhardt related changes in plant growth to pollutants when he attributed spruce and fir injury to sulfur dioxide from a smelter (cited in Brandt, 1987). In 1955, Gorham stated that acidic precipitation could acidify lakes, streams, and soils (cited in Binkley et al., 1989).

In the early 1970s, chlorosis and crown-thinning of silver fir in southern forests of the Federal Republic of Germany were reported (Brandt, 1987). The symptoms typically progressed from defoliation to death. In the mid-1970s, similar symptoms were observed in widely distributed stands of Norway spruce. Damage to deciduous trees (European beech and oak) has also been observed since 1981. In the 1970s, because of concern over both this apparent new decline (i.e., affecting many species) and the potential effects of acid rain on aquatic systems, attention focused on acidic deposition as the primary cause. More recently, other contributing factors have been suggested, such as soil and foliar nutrient deficiency, tree harvesting, pathogenic fungi, and drought (Blank et al., 1988).

From 1980 to 1984, reports of spruce disease have also come from other parts of central Europe, southern Scandinavia, and northern Italy (United Nations Environment Program, 1987). Initial projections of increasing damage leading to destabilization of forest ecosystems have not been supported (Blank et al., 1988).

In North America, Packard reported in 1884 on spruce mortality that was due to insects in New York and Maine. According to Blais (1983), spruce budworm outbreaks in eastern Canada have occurred periodically for 300 years. He related increased outbreak severity to human interventions such as clearcutting, fire protection, and pesticides.

Surveys of spruce-fir forests at high elevations (above 800 m) in the northern Appalachian Mountains in the late 1960s and early 1970s indicated either declines in growth rates or increases in mortality of red spruce and balsam fir (Johnson and Siccama, 1983; Scott et al., 1984; Vogelmann et al., 1985). At lower elevations over most of the northeastern United States, a decline in radial increment of red spruce beginning about 1960 was also reported (Hornbeck and Smith, 1985). A similar growth-trend decline since the 1960s has been reported for red spruce in the mid-Appalachians (Adams et al., 1985) and southern Appalachians (Bruck, 1984; McLaughlin et al., 1987). With respect to mortality observed in the southern Appalachians, most was Fraser fir that had been killed by the balsam woolly adelgid (Johnson and Siccama, 1983; Bruck et al., SF02-2; Zedaker et al., SF25-4).

Average annual radial growth rates of southern pines less than approximately 41 cm (16 in) in diameter have declined 30% to 50% over the past 30 years (Sheffield et al., 1985). This decline was reported for natural stands in the Piedmont and mountain regions of South Carolina, the Piedmont region of Georgia, and coastal plain areas of Georgia and South Carolina.

Millers et al. (1989) reviewed mortality in eastern hardwood forests over the last century. They reported that many species showed declines and mortality and that the incidence has increased in the last few decades. Most mortality could be attributed to weather, silviculture, or insects and pathogens, and the increase in reports of decline was attributed to more consistent reporting and forest maturation.

Miller (1984) related increased mortality of ponderosa and Jeffrey pine to ozone concentrations in the San Bernardino Mountains of California. Recent trends of tree condition in the San Bernardino National Forest indicate decreased crown injury. Ponderosa and Jeffrey pine have shown visible symptoms of damage in the Sierra Nevada Mountains; the growth index of large-diameter Jeffrey pine growing on poor sites exposed to ozone has decreased 11% since 1965 (Peterson et al., 1987).

2.4 FRP Research Methods

Most of the research funded by the FRP began during the summer of 1986. The research presented in MPO #1&2, MPO #3, and in this document used two conceptual approaches to address the policy questions: epidemiological and physiological.

The epidemiological approach is characterized by surveys of forest condition conducted to identify patterns that may be related to atmospheric deposition or other environmental factors. This approach addresses Policy Question #1, and, indirectly, Policy Question #2. Several types of epidemiological studies were funded by the FRP, including surveys of forest growth, mortality, and crown condition, dendroecological studies, and atmospheric deposition monitoring. Air quality measurements were also made at a number of sites.

The physiological approach is characterized by experimental studies of the effects of particular environmental variables on the health of individual trees or stands, and it addresses Policy Question #2. The physiological studies were primarily controlled exposures of pollutants on experimental material to identify correlations and to test the hypothesized mechanisms of cause and effect. Tree seedlings were the most common experimental material, but branches of mature trees, mycorrhizae, and forest soils were also studied. Treatments were applied under varying environmental conditions ranging from growth chambers to open-top field chambers to field manipulations. Growth responses and physiological effects were determined for a wide range of tree species in relation to quantified exposures of pollutants.

2.5 Summary of MPO #1&2

In MPO #1&2, Reams et al. (1990) addressed the two scientific questions of Policy Question #1: 1) whether recent changes in forest condition are greater than what would be expected from natural variability; and 2) whether spatial patterns in forest condition are related to spatial patterns of pollutant exposure. Reams et al. concluded that in two forested areas studied by the FRP, significant changes in forest condition may be related to pollutant exposure. In this section, we present the conclusions of Reams et al. regarding the status of forests and spatial patterns in forest condition and pollutant exposure.

2.5.1 Changes in Forest Condition

In answering the first scientific question based on the research presented in MPO #1& 2, two regions were identified as showing changes in forest condition. First, the incidence of ponderosa pine foliar injury in the southern Sierra Nevada of California is greater than would be expected from natural sources of variability. Second, in the Northeast, high-elevation red spruce showed increased mortality in the 1960s. However, it is not known if the proportion of standing dead red spruce is outside the range of natural variability.

2.5.2 Spatial Patterns in Forest Condition and Pollutant Exposure

To most effectively evaluate the second scientific question, Reams et al. concluded that both forest condition and deposition levels should be known at the location of interest. Since deposition monitoring typically is not conducted at the same sites at which forest condition is assessed, pollutant levels at the forest plots of interest had to be estimated. Reams et al. suggested that the variability of these estimates is either unknown or quite large, such that only plots that are a great distance apart have significantly different estimated deposition levels. Identification of spatial patterns in deposition over time was further limited because historical data extend back only to the late 1970s, and patterns vary greatly from year to year. Thus, there has been limited success in answering the second scientific question.

These problems notwithstanding, spatial patterns of changes in forest condition and increased pollutant exposure were determined to exist in the two regions identified in answering the first scientific question. In the southern Sierra Nevada of California, injury to ponderosa pine needles is consistent with symptoms typical of ozone injury, and injury is found in areas with elevated levels of ozone. Second, the percentage of red spruce standing dead basal area increases with increasing elevations in the Adirondack and Green Mountains of the northern Appalachians. These increases are consistent with increasing levels of wet deposition.

2.6 Summary of MPO #3

In MPO #3, Peterson et al. (1989) summarized the results of controlled exposures of sulfur dioxide, simulated acidic deposition, and controlled exposures of ozone on seedlings conducted by the FRP through 1988. Peterson et al. concluded that although there are currently no data on the long-term effects of multi-year pollutant exposures on seedlings, differential changes in above- versus belowground biomass in response to short-term pollutant exposures indicate long-term problems for seedlings. Under chronic exposure, eventual tree productivity or survival could be affected. In this section, we summarize the conclusions of MPO #3.

2.6.1 Effects of Sulfur Dioxide

Increased concentrations of sulfur dioxide (up to 66 ppb) caused several changes in growth and carbon allocation patterns during controlled exposures using western conifer seedlings. Changes included increased aboveground growth for Engelmann spruce, white fir, western red cedar, and Douglas-fir; reductions in root biomass and root/shoot ratios for Douglas-fir, ponderosa pine, and lodgepole pine; and increased bud elongation for ponderosa pine, Douglas-fir, western hemlock, and western red cedar. The altered post-exposure growth and imbalance in above- and belowground responses indicated changes in carbon allocation patterns.

2.6.2 Effects of Acidic Deposition

The clearest response to increased acidity was reduced frost hardiness of current-year needles in red spruce seedlings. The seedlings were exposed to simulated acidic mists during the growing season, and twigs were exposed to simulated frosts during the autumn hardening period.

Although individual species showed some effects of short-term exposures to simulated acidic deposition, these results cannot be generalized for all species tested. For example, growth of black cherry was decreased by pH 3.0 versus 4.2. Furthermore, increased aboveground growth coupled with no apparent effects on belowground biomass in western conifers at pH 2.1 compared with pH 5.6 indicated changes in carbon allocation patterns. Most of the species that were tested at pH levels below 3.0 showed some visible injury.

2.6.3 Effects of Ozone

The direct effect of ozone varied from suppressed growth of loblolly pine, ponderosa pine, and some hardwood species to physiological changes in the foliage of red spruce. Stem and root growth of loblolly pine was reduced at 80 ppb or higher. At intermediate levels (40 to 80 ppb) results were more variable, and it was not uncommon for growth rates to be greater than those in charcoal-filtered air. Net photosynthetic rate of loblolly pine showed cumulative decreases in response to increased exposure to ozone. Several growth measures of ponderosa pine were reduced while most other western conifer species showed increased growth rates at levels less than 100 ppb. Ponderosa pine, white fir, subalpine fir, and western hemlock also showed visible injury in response to ozone at 70 ppb. Growth of black cherry, white oak, red maple, and yellow birch was reduced at concentrations above 70 ppb. Yellow-poplar, white ash, and red oak displayed no growth response at the same levels. Most eastern hardwood species showed visible injury with exposure to ozone of 70 ppb or higher. Yellow-poplar, yellow birch, sweetgum, red maple, white ash, and black cherry appeared to be the most sensitive to foliar injury of the species tested. Damage to foliar mesophyll cells, decreased photosynthetic pigments, and seasonal changes in photosynthesis in red spruce occurred in response to ozone at 40 ppb and higher.

2.7 Summary of Atmospheric Deposition and Pollutant Exposure

Networks of monitoring sites have been established to characterize the concentration and deposition of atmospheric pollutants in forests. The principal monitoring networks in the United States are the National Atmospheric Deposition Program/National Trends Network (NADP/NTN) and the Mountain Cloud Chemistry Program (MCCP) of the Atmospheric Research Cooperative. Figures 2 and 3 present pH and sulfate (SO_4^{2-}) wet deposition for the United States. Dry deposition (and cloud deposition at high elevations) can add considerably more total sulfur (S) deposition than that shown in Figure 3. For example, dry S deposition accounted for 40% to 60% of total S deposition at low-elevation forested sites in the southeastern United States and for 10% to 40% at most other low-elevation forested sites in North America (Lindberg, 1989). At a high-elevation forest site in the Smoky Mountains, NC, and a high-elevation forest site at Whiteface Mountain, NY, approximately 50% of total SO_4^{2-} deposition was due to cloud water interception by the forest canopy (Lindberg, 1989).

The MCCP consists of one low-elevation monitoring site at Howland, ME, and five high-elevation sites that experience frequent cloudiness: Whiteface Mountain, NY, Mt. Moosilauke, NH, Shenandoah, VA, Whitetop Mountain, VA, and Mt. Mitchell, NC (see Figure 4). The data collected include cloud water concentrations of the following ions: SO_4^{2-}, nitrate (NO_3^-), chloride (Cl^-), hydrogen (H^+), ammonium (NH_4^+), sodium (Na^+), magnesium (Mg^{2+}), potassium (K^+), and calcium (Ca^{2+}). At all sites, liquid water content is measured; aqueous hydrogen peroxide (H_2O_2) also is measured in some samples. Data have been collected from April to October in 1986 through 1988.

Precipitation concentrations of acidifying compounds in the United States are lower (i.e., higher pH) than levels shown to be harmful to seedlings (see Figures 2 and 5 for data on the concentrations, and MPO #3 for data on seedling exposure). In contrast to precipitation, cloud water collected at the five MCCP sites had pH levels below 3.3 from 10% to 40% of cloudy hours. These

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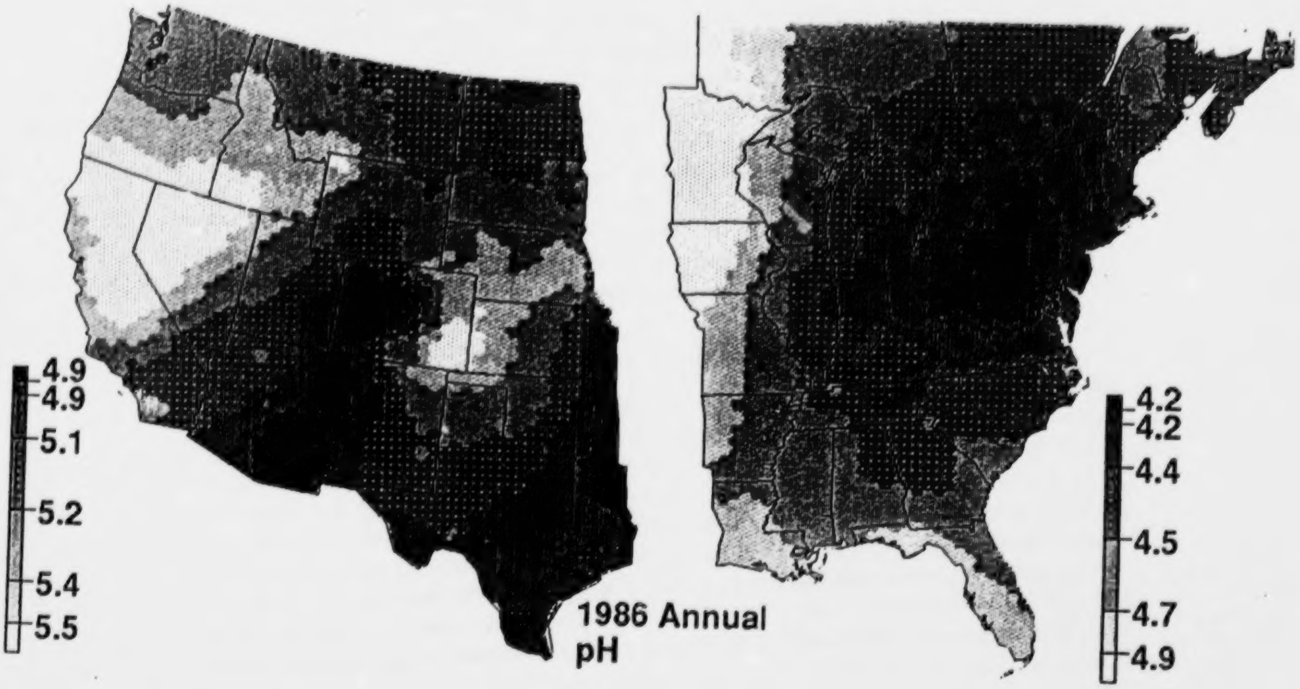

4.9
4.9
5.1
5.2
5.4
5.5
1986 Annual
pH
4.2
4.2
4.4
4.5
4.7
4.9

Figure 2. Annual volume-weighted mean pH in precipitation for 1986. Note that shading is different for eastern and western regions (Olsen, 1989).

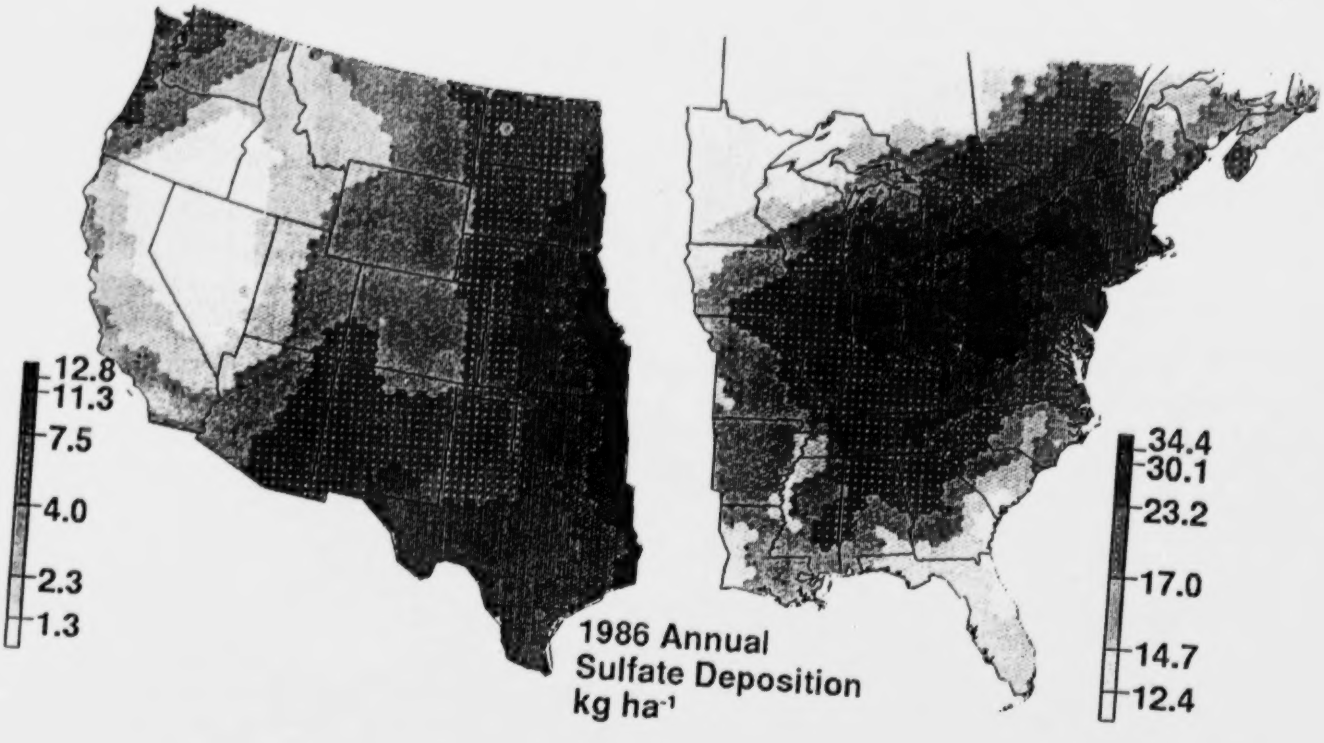

12.8
11.3
7.5
4.0
2.3
1.3
1986 Annual
Sulfate Deposition
kg ha⁻¹
34.4
30.1
23.2
17.0
14.7
12.4

Figure 3. Annual SO_4^{2-} wet deposition via precipitation for 1986 (kg/ha). Note that shading is different for eastern and western regions (Olsen, 1989).

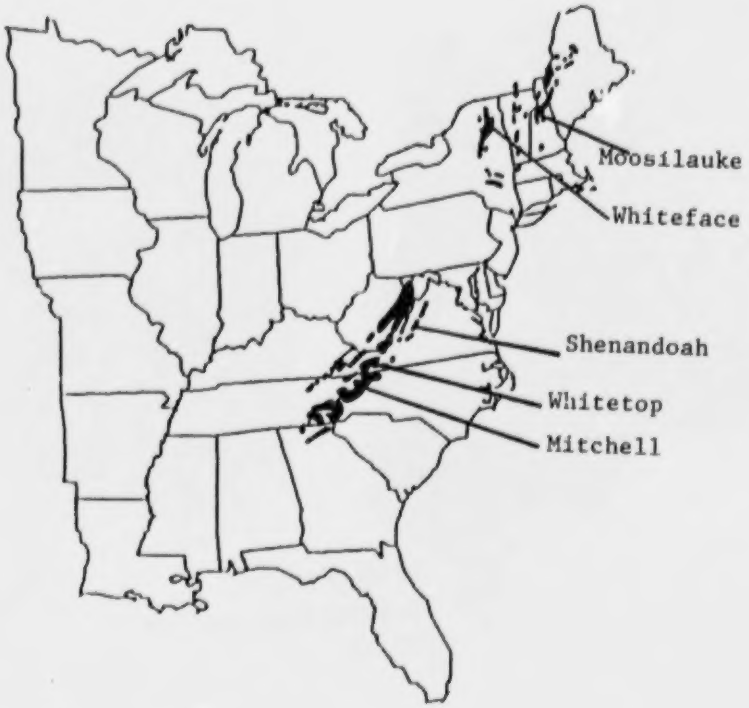

Moosilauke
Whiteface
Shenandoah
Whitetop
Mitchell

Figure 4. Land areas above mean cloud base in the eastern United States that receive significant cloud droplet deposition. (High-elevation MCCP sites are indicated.)

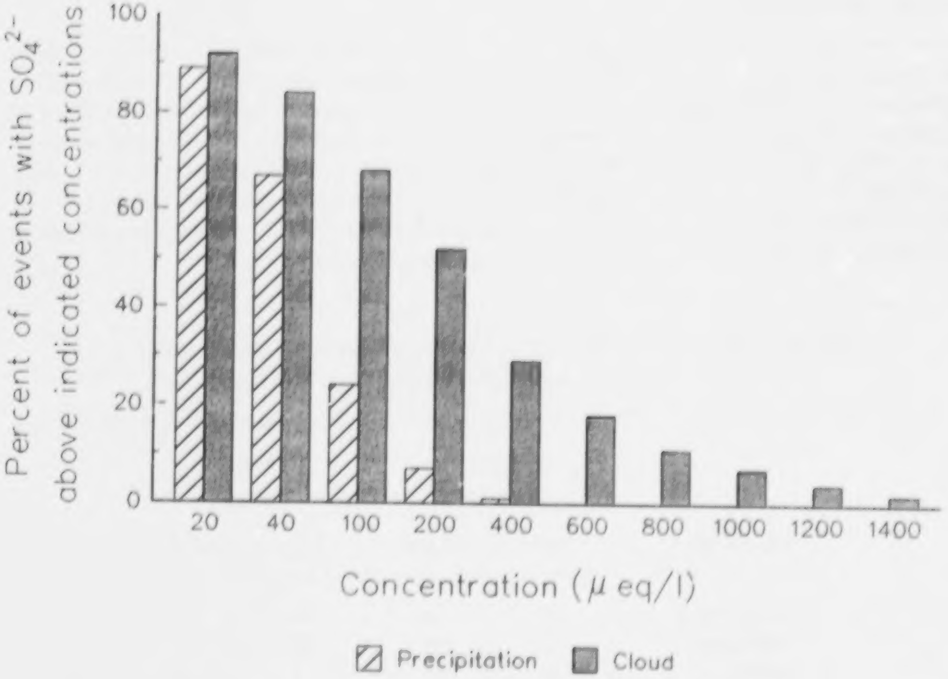


Figure 5. Comparison of SO_4^{2-} concentrations in cloud water and rain water. (Data are from cloud samples at Whiteface MCCP site and precipitation samples at Whiteface MAP3S site).

levels are within the range shown to reduce frost tolerances of red spruce seedlings (Peterson et al., 1989).

The MCCP results also indicate that chemical deposition to forests is greater at higher elevations than at lower elevations due to interception of clouds. Generally, cloud deposition contributes a much smaller proportion of input at low elevations than do dry and precipitation deposition. Two factors regulate the amount of chemical deposition from clouds: the amount of cloud water deposited and the concentrations of chemicals in the clouds. Frequency of cloudiness increases with increasing elevation (see Figure 6). Cloud base height is typically between 800 and 1200 m in the Appalachian Mountains (Vong, 1989; Mohnen, 1988a,b). Therefore, high-elevation sites are reasoned to have greater amounts of deposition than lower elevations. With respect to chemical concentrations, the aqueous concentrations of the major ions (NH_4^+, H^+, SO_4^{2-}, and NO_3^-) typically are higher in clouds than in precipitation (see Figure 5) by factors ranging from 5 to 20, depending on location in the Appalachians.

Increasing cloud water interception by forest canopies should occur with increasing cloud frequency (see Figure 7). Comparison of Table 3 with Figure 3 suggests that cloud water SO_4^{2-} deposition (21 to 140 kg/ha/yr) is often greater than SO_4^{2-} deposition via precipitation (25 to 35 kg/ha/yr). Cloud water deposition estimates are too uncertain to detect spatial patterns across peaks within the Appalachian Mountain range. However, a sharp vertical gradient in total deposition (sum of wet, dry, and cloud) exists when comparing forests below cloud base with those frequently immersed in clouds at one mountain. Therefore, with increasing elevation above cloud base, increasing cloud water interception by foliage occurs.

Table 3. Range[a] of published estimates of SO_4^{2-} and water deposition from intercepted cloud water[b] (from Vong, 1989; Mohnen, 1988a)

	SO_4^{2-} (kg/ha/mo)		Water (cm/yr)	
MCCP Site	Low	High	Low	High
Moosilauke	2	12	18	68
Whiteface	2	11	13	127
Whitetop	8	13	-	25-26
Mitchell	5	10	32	35-77
Shenandoah	1	1	5	9
Smokies	3	4	15-80	37

[a] Range is a function of variation in cloud frequencies, elevations, and uncertainties in the Lovett model (1984).

[b] Cloud water flux was determined by: 1) a version of the Lovett model (1984); or 2) collecting throughfall under the canopy and correcting for precipitation and evaporation.

2.8 Ozone Exposure

At rural, low-elevation, forested sites in the northeastern United States, the Great Lakes region, the Ohio River valley, and the southeastern United States, daytime (0900-1559 hr) average

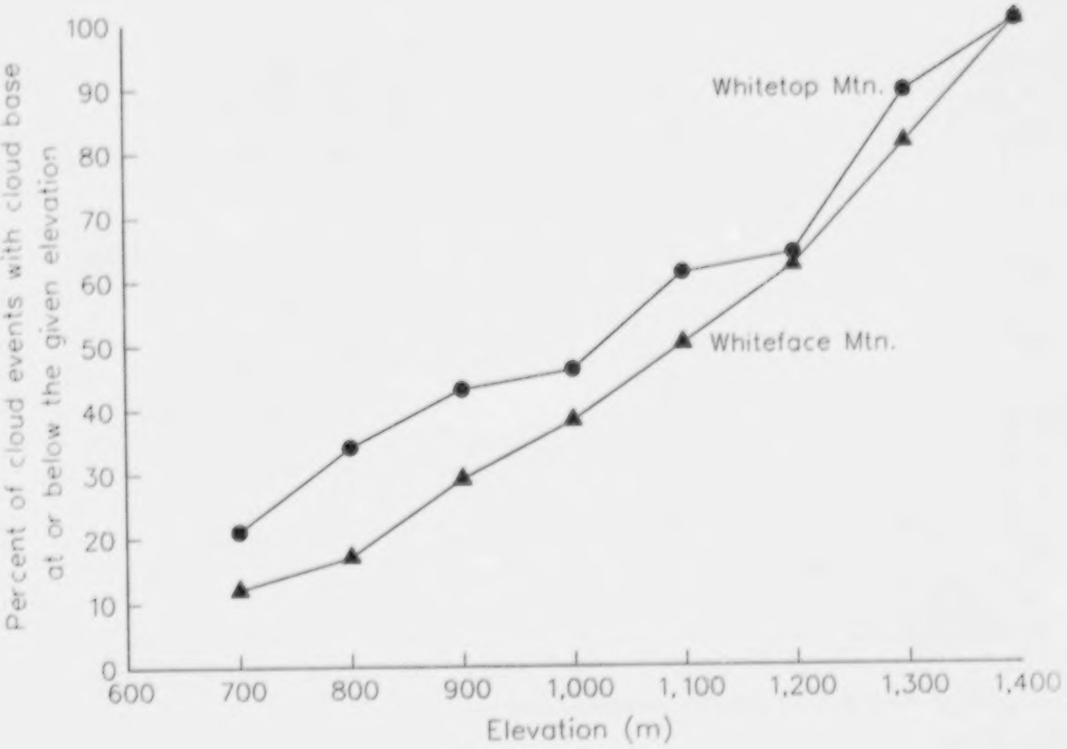


Figure 6. Cloud frequency by elevation during growing season for two MCCP sites. (Total cloud impaction frequencies at the summits are 28% and 42% of all hours for Whitetop Mountain and Whiteface Mountain, respectively)(Vong, 1989).

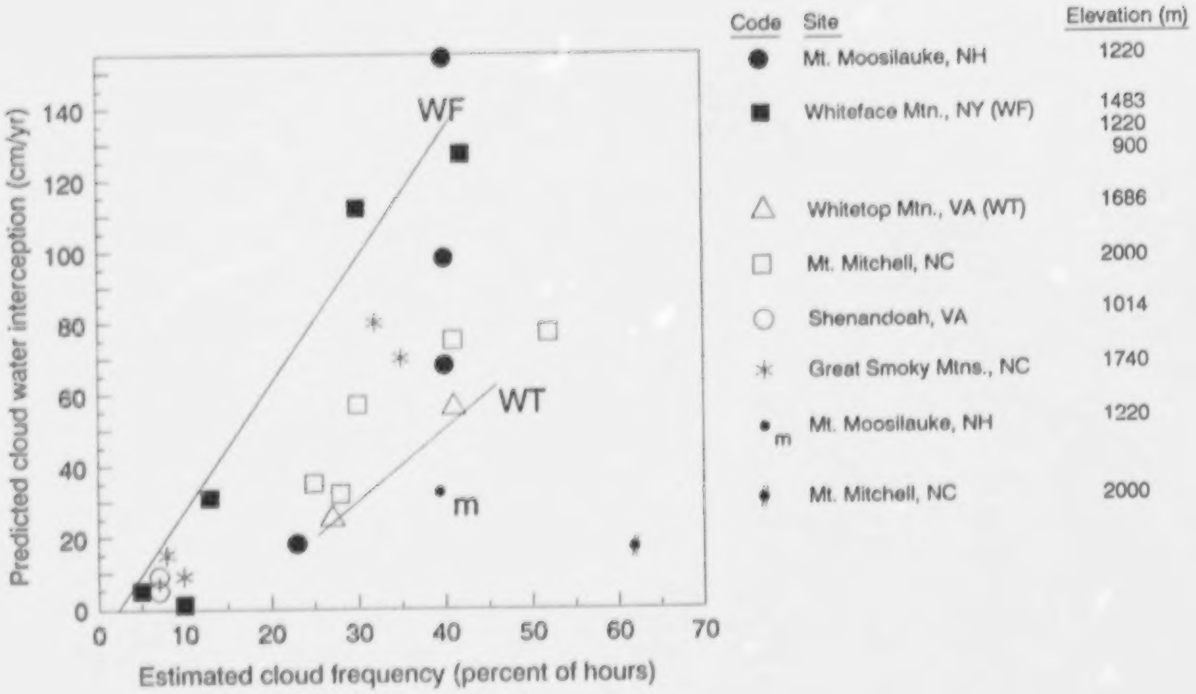


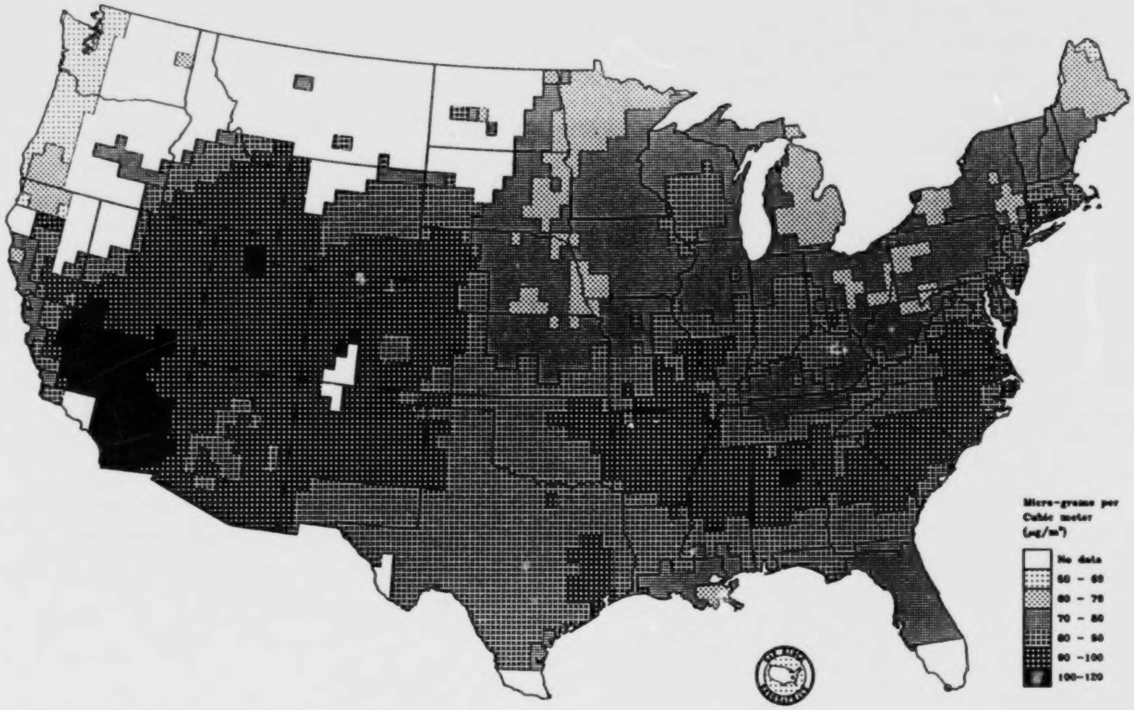
Figure 7. Published values for cloud frequency and predicted water interception. The lines approximately describe this relationship for a site with low liquid water content and low wind speed (Whitetop Mountain) and high liquid water content and high wind speed (Whiteface Mountain)(from Hicks et al., 1989).

ambient ozone (O_3) concentrations during the growing season typically ranged from 35 to 55 ppb during 1978-1985 (Lefohn and Pinkerton, 1988; Pinkerton and Lefohn, 1987). Peak concentrations over 100 ppb were not unusual. Garner et al. (SC01-2) reviewed ambient exposure data from Whiteface Mountain, NY, and stated that similarly high one-hour peak concentrations (i.e., 100 ppb) have been observed in most years between 1975 and 1984 (Lefohn and Mohnen, 1986; Mohnen, 1987). Garner et al. also noted that because O_3 showed little diurnal variation at high-elevation sites, forests at these elevations are exposed to high O_3 concentrations for more consecutive hours than are forests at low elevations.

Lefohn and Pinkerton (1988) extended their analysis to include sites along the northwest Pacific Coast. The daytime O_3 concentration for this region over the 1978-1985 growing seasons averaged 31 ppb. However, a more detailed analysis of the western sites for 1980-1987 has been done by Böhm (1989). Concentrations between 60 and 80 ppb occurred between 5% and 25% of the measured hours at most sites except those in the Pacific Northwest where O_3 is lower. The San Bernardino Mountains in California are exposed to O_3 concentrations over 100 ppb during 10% of measured hours during summer.

Spatial patterns of ambient O_3 concentrations across the continental United States for 1978-1983 were produced by kriging as part of the NAPAP Interim Assessment (Figure 8). Data from the EPA Storage and Retrieval of Aerometric Data (SAROAD) database were selected to minimize urban influences. Concentrations were calculated as 7-hr means (0900-1559 local standard time) for April through October to reflect typical growing season O_3 levels. A kriging algorithm was used to interpolate from the randomly located sites to a 0.5° latitude by 0.5° longitude grid (Reagan, 1984). Areas that did not have monitoring sites within 30 km of at least five stations in a 500-km^2 area were excluded, as was the Los Angeles Basin.

General regional patterns in Figure 8 indicate that areas in southern and central California, the high desert and intermountain region of the West, and the southcentral East and midwestern states were more likely to be exposed to elevated O_3 levels than were other areas. However, the patterns in Figure 8 may reflect errors inherent in spatial kriging, such as violation of the stationarity assumption (Delhomme, 1978), which assumes that sites located closest to each other have the most similar concentrations. At present, the high concentrations shown in the much of the interior West are thought to be somewhat higher than actual.


Micro-grams per
Cubic meter
(µg/m³)
No data
50 - 60
60 - 70
70 - 80
80 - 90
90 -100
100-120

Prepared by Geographic Data Systems in Cooperation
with Environmental Sciences Division, ORNL

Figure 8. Ambient O_3 concentrations ($\mu g/m^3$) expressed as 7-hr means, for April-October, 1978-1982 ($1 \mu g/m^3$ of O_3 = 0.51 ppb of O_3).

3 RESULTS AND DISCUSSION

To aid in synthesizing the diverse FRP research projects, tables have been prepared to summarize findings of individual studies. This summary shows the breadth of research and allows the reader to compare results of studies. Since the tables are long and are referred to repeatedly, they are located in Appendix E. The reports summarized in the tables vary from published manuscripts to comprehensive annual reports to briefer research summaries that included only preliminary interpretations. In the tables and in the body of the report, all FRP reports, published or unpublished, are referred to by the first author followed by a report number. The report number consists of two letters that indicate the research cooperative that funded the research, the project number, and a number identifying the report (e.g., SF04-5 or EH12-1). These report numbers are also included in the Literature Cited section.

The first table (Table 4) summarizes the controlled exposures of acidic precipitation and O_3 on seedlings. The remaining tables group studies of similar types, highlighting the basic methods and findings of each. The main conclusions of the authors as they pertain to the scientific questions are listed in boldface. In cases where conclusions were not provided by the authors, we have provided our conclusions. The authors have reviewed the tables and changes were made based on their comments.

Table 4 shows the general trend of the seedling response with respect to the control or lowest level of treatment. We report the response qualitatively as positive (+), negative (-), or no (0) response. In determining whether a response was positive or negative, our criterion was more liberal than many of the authors, who typically relied on statistical tests with $\alpha = 0.05$. If a consistent trend was evident in the data, yet no significant treatment differences were found (perhaps because the power of the test was low), we report a response and indicate that our interpretation differed from the authors'. Scanning down a particular column gives an impression of the overall response of a class of seedlings to acidity or O_3. Although this may be less informative than a quantitative description of response for each individual study, the purpose of the tables is simply to present general findings from numerous studies that were designed with different objectives in mind. Individual reports must be referred to for a more complete description of the response. Alternatively, MPO #3 (Peterson et al., 1989) presents the seedling responses for individual studies in greater detail for studies up to February, 1989.

Tables 5 through 10 present the results of other research, grouped by type of study (e.g., soils and nutrient cycling in Table 5 and forest condition studies in Table 7) or by the scientific question that is being addressed (e.g., winter injury findings in Table 8). The tables have a similar format, showing study type, variables collected, findings, and general interpretations or relevance of the study. Table 11 lists conclusions from FRP-sponsored literature reviews and syntheses.

The explanation and discussion of results has been organized according to the scientific questions identified for Policy Question #2. Each scientific question did not receive equal emphasis in the FRP research projects, and our tables and discussion reflect the emphasis each question received.

We discuss the results in the order of the listing of the scientific questions in Table 2. For each question, we first present and discuss FRP findings. We then discuss non-FRP research where it provides additional information that addresses the question. The non-FRP research was generally from ongoing programs that parallel the FRP; these include programs funded under NAPAP, such as the Direct/Delayed Response Program (DDRP), and nongovernmental efforts by groups such as the Electric Power Research Institute (EPRI) and NCASI.

3.1 Soil Chemistry and Nutrient Cycling

Soil studies may only indirectly assess whether changes in chemical properties of natural soils can be caused by atmospheric deposition because no suitable controls are available and because changes typically occur over long time periods. However, some consensus may be reached by evaluating several types of studies simultaneously. We examine four types of soil studies:1) studies conducted along regional atmospheric deposition gradients; 2) studies along elevation transects where deposition above cloud base (800 to 1200 m in the Appalachian Mountains) is two times greater than it is below cloud base; 3) experimental additions of acids to soils; and 4) literature reviews and modeling projections.

3.1.1 Trends Along Regional Deposition Gradients

Along large-scale gradients of increasing SO_4^{2-} deposition in hardwood forests (compare Figure 9 with Figure 3), four projects have produced data demonstrating that soil chemical properties or nutrient cycling vary spatially in a manner consistent with spatial patterns of acidic deposition and associated compounds. These results are discussed briefly in the following paragraphs and are summarized in Table 5.

Along a gradient of increasing SO_4^{2-} deposition from western Minnesota to Michigan, in 169 plots distributed among five forest types, a pattern of increasing S was observed in the soil and in the organic forest floor lying above the mineral soil (David et al., VS10-7). David et al. observed this pattern after first adjusting S using nitrogen (N) concentrations as a covariate. Thus, this pattern in S means that the S:N ratio increases along the deposition gradient. Along this same gradient, increasing lead (Pb) and cadmium (Cd) in the forest floor were observed (Grigal and Ohmann, VS10-3). Grigal and Ohmann also observed a decrease in cations in the forest floor along the gradient of increasing S deposition. However, they believed the cation pattern was more likely due to wind deposition of soils from more westerly sources.

Increases of S in sugar maple foliage and of S and N in litterfall (Figure 10)(Pregitzer et al., EH03-4) and increases in soil S and soil S leaching (Figure 11)(Witter, EH03-7) were observed across five sites in the sugar maple forests distributed along a second SO_4^{2-} deposition gradient from northeastern Minnesota to Michigan. The sites used by Witter and Pregitzer et al. were selected so that deposition of SO_4^{2-} increased by about 5 kg/ha/yr between successive sites from Minnesota to the southeastern region. After this criterion was met, 15 plots were selected (three per site) controlling for three variables: 1) landform (glaciated, mesic uplands with slopes of 0-20%; south slopes were avoided except in two plots); 2) soil texture (sand-loam A horizons, distinct E horizon, and sand B horizon); and 3) vegetation (sugar maple overstory with mean age of 55-75 yrs, no obvious disturbance). The effort invested in locating analogous stands strengthens the argument that long-term deposition patterns of S and N may be involved in influencing nutrient cycling in these forests. A number of other patterns in nutrient chemistry are noted in in the entry for Witter et al, in Table 5; however, SO_4^{2-} deposition does not appear to be affecting these patterns. Research is still continuing, but no change in forest growth or mortality has been observed along the gradient (Witter et al., EH03-2, Table 7).

A decrease in soil pH, a decrease in exchangeable soil calcium (Ca), and an increase in soil C (Figure 12) were observed in the A1 horizon of soils along a gradient of increasing SO_4^{2-} deposition across seven sites from Arkansas to Ohio (Table 5, Loucks and Somers, EH05-6). In addition, exchangeable aluminum (Al) was higher at sites with a high ratio of equivalents of SO_4^{2-} deposition to equivalents of total soil basic cations. Precipitation decreases along the Ohio corridor gradient from west to east (130 versus 100 cm annual average; O. Loucks, personal communication). Thus, these results contradict the view that soil C increases with precipitation (Brady, 1974; Oades, 1988), and Loucks and Somers concluded that acidic deposition may have reduced rates of surface layer decomposition processes. Plots in the Ohio gradient were selected

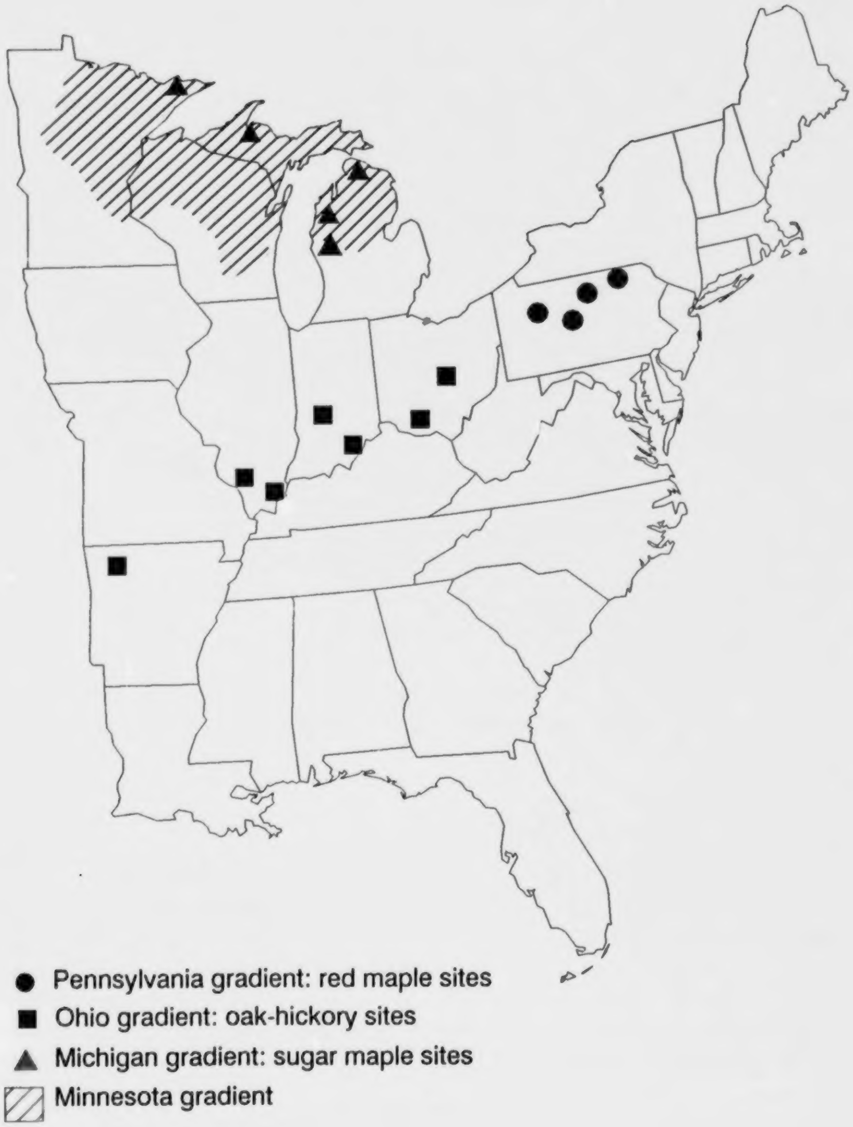

● Pennsylvania gradient: red maple sites
■ Ohio gradient: oak-hickory sites
▲ Michigan gradient: sugar maple sites
▨ Minnesota gradient

Figure 9. Forested regions studied by the FRP in the eastern hardwoods. (Refer to Figure 3 for SO_4^{2-} deposition patterns.)

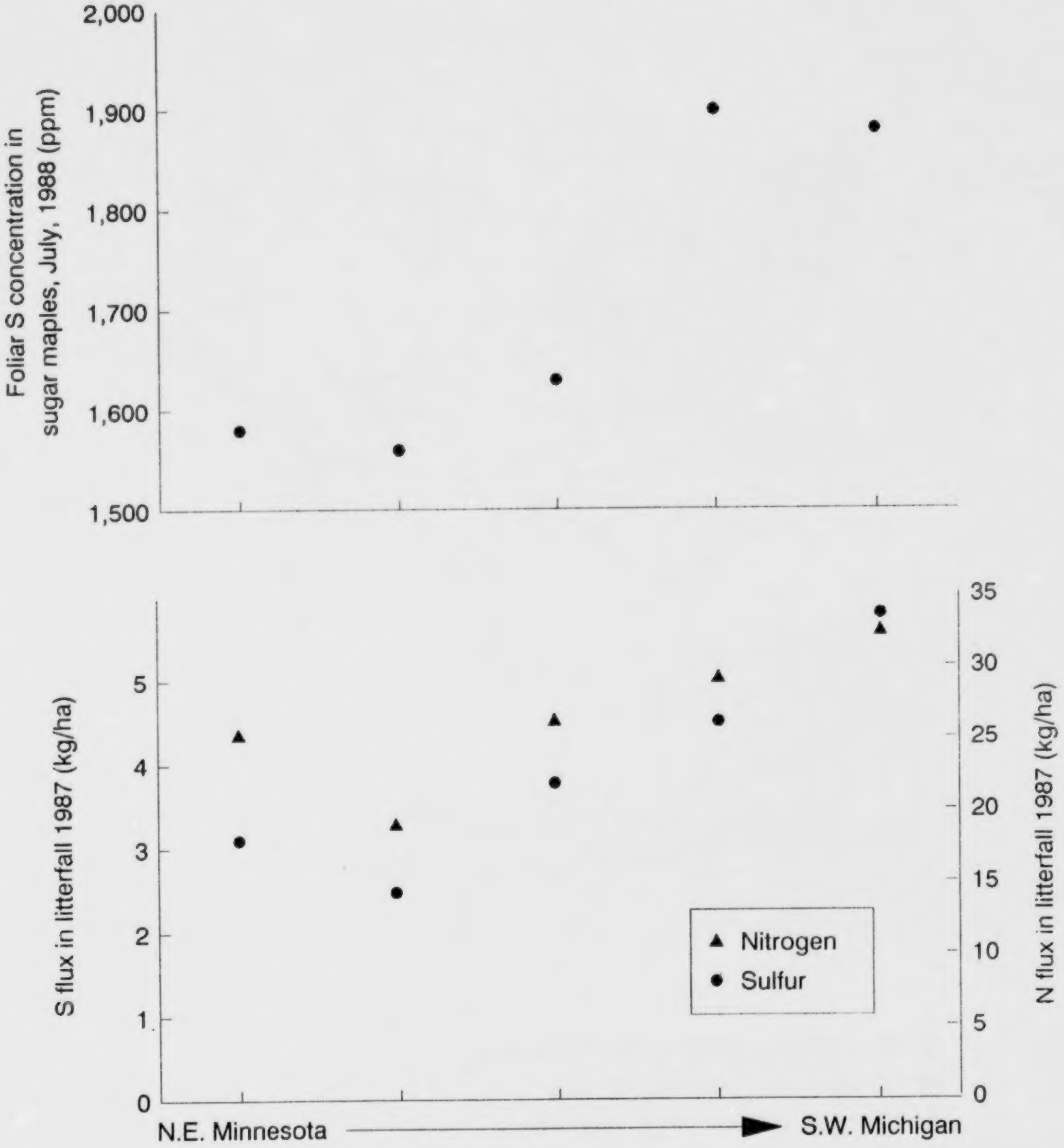


Figure 10. Foliar S concentrations in sugar maples and S and N flux in litterfall (all species) at sites along the Michigan gradient (from Pregitzer et al., EH03-4). (Refer to Figure 9 for site locations.)

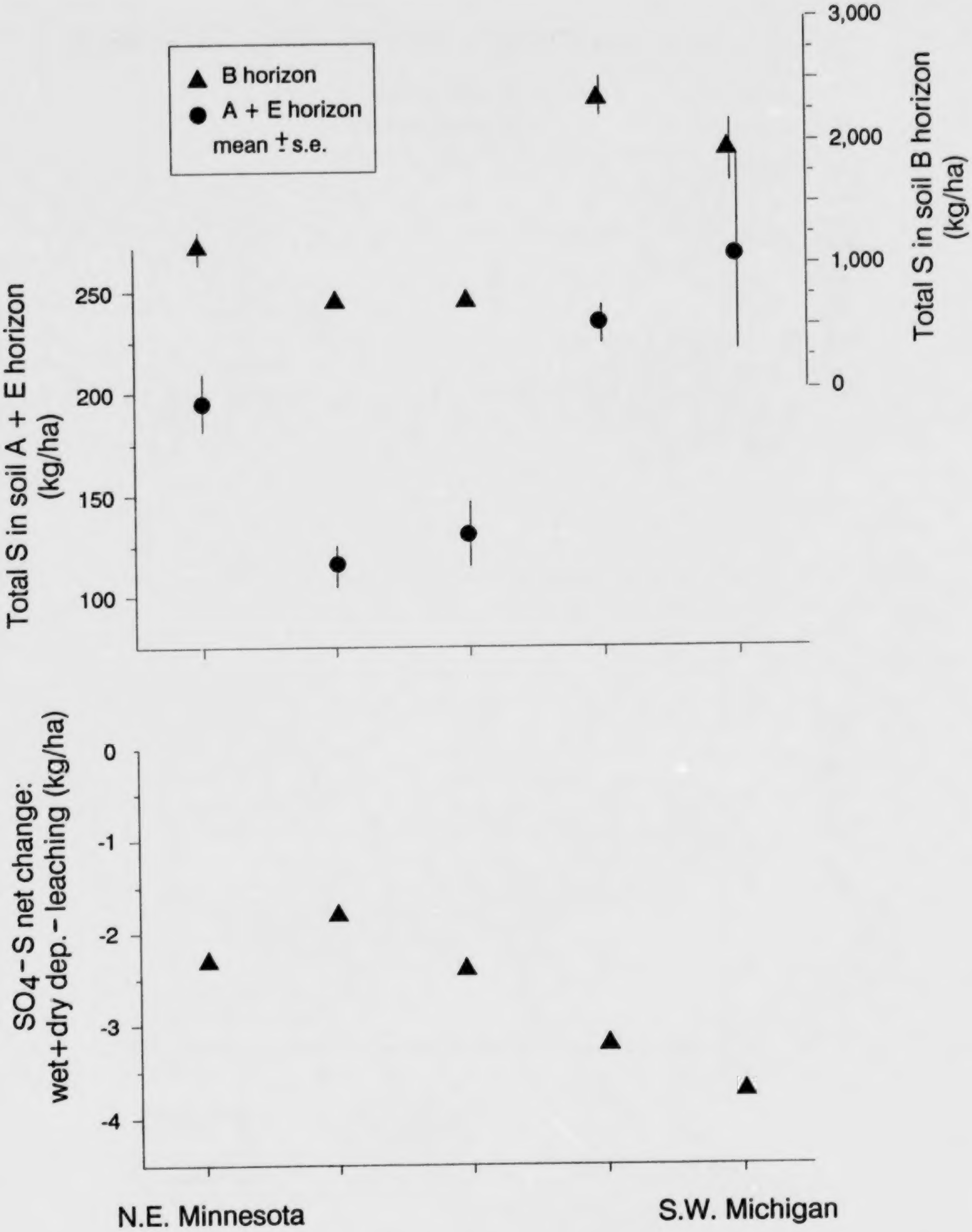


Figure 11. Soil S pools and net SO_4^{2-} loss below the B horizon from Michigan gradient sites. Soil nutrient flux was calculated using an estimate of evapotranspiration of 42% for all sites (from Witter et al., EH03-7). (Refer to Figure 9 for site locations.)

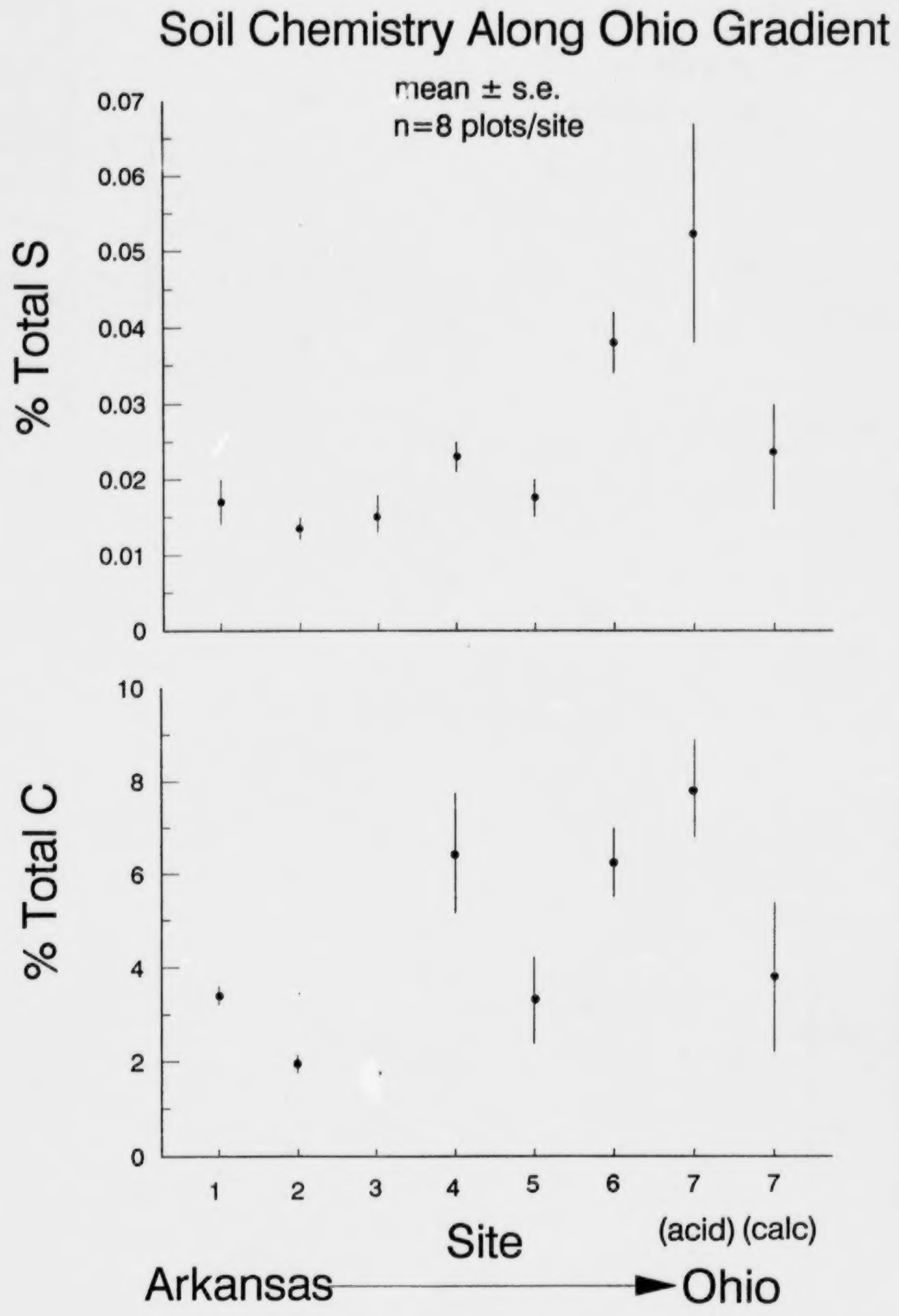


Figure 12. Total S and total C in the Al horizon of siliceous, sandstone-based soils in sites along the Ohio gradient. (Refer to Figure 9 for site locations.) Site 7 is displayed on acid soils (4 plots) and on calcareous soils (4 plots); the plots on calcareous soils are not comparable to the remaining sites (from Loucks and Somers, EH05-6).

to be as analogous as possible; eight plots per site were selected on unglaciated and poorly buffered soils, on mostly southerly and upper slope positions, supporting oak and hickories typically from 75-130 years of age. It was recognized that deposition at a site would vary as a function of both rainfall differences due to local topography and distance from local sources of SO_2 emissions (coal-burning power plants). The three sites near the Ohio River were in closer proximity to local sources of SO_2 compared with three sites to the north (Figure 9). Effects of these local sources of SO_2 have not yet been analyzed, but the regional trend in soil S is in the same direction as that reported by David et al. (VS10-7) and Witter et al. (EH03-2).

Loucks and Somers [EH05-6] attempted to examine whether their observed trend of decreasing pH and increasing soil C with increasing SO_4^{2-} deposition along the Ohio gradient is a recent phenomenon. They compared their data to county soil survey data of similar soils collected during the 1960s and 1970s. The county soil survey data indicated no trend in either pH (mid-range among the sites varies from pH 4.9 to 5.4) or percent C (mid-ranges vary from pH 1.4 to 3.2). The pH values of Loucks and Somers tend to be lower than values from the 1960s and 1970s at all sites (medians vary from pH 3.9 to 4.6), whereas the C values are higher at the eastern sites (means vary from 4.5 to 7.8%). Comparisons of pH values or percent C between the two data sets should be made with caution since Loucks and Somers did not determine what portion of the differences could be due to differences in methods.

Preliminary analyses of forest condition along the Ohio gradient indicate that subtle changes may be occurring. Mortality rates of larger trees have increased in the last decade; however, the rates still appear to be quite low and no spatial patterns exist (Loucks et al., EH05-8)(Table 7). On sites with low Ca:Al ratios, radial growth of black oak and white oak has declined since 1960 (LeBlanc, EH05-7)(Table 7).

Along a deposition gradient in Pennsylvania, soil exchangeable magnesium (Mg) and Ca were correlated with atmospheric deposition of Mg and Ca. Sap concentrations of Mg and Ca in red maple stems were also correlated with deposition patterns (McCormick, EH04-3). Similarly, there was a strong association between sap N concentrations and levels of atmospheric N deposition. This suggests that nutrient cycles in the soil and in the trees are responding to atmospheric deposition.

In summary, several trends have been reported in nutrient cycling or soil chemical properties along regional gradients of SO_4^{2-} deposition. The same variables were not measured in all studies, making it difficult to reach a common conclusion. However, three studies measured some aspect of soil S, and all observed an increase with increasing SO_4^{2-} deposition. Increased S suggests that deposition can have measurable effects on nutrient cycling. While these types of studies cannot establish cause, these findings do establish a relationship between atmospheric deposition and soil chemical properties.

If SO_4^{2-} deposition is causing increases in soil S availability and cycling within the forests, a number of possible responses may be expected. Along with S, increased N and hydrogen (H) deposition also occurs (Reams et al., 1990). Soil nutrient availability may be increased due to the inputs of S and N and due to increased weathering of basic cations. As deposition of anions increases to levels exceeding plant uptake, leaching below the root zone will occur because soils have low anion retention capacities (Bohn et al., 1979). Anion leaching will act to remove basic cations, causing some reductions in soil pH. But S deposition alone will not acidify soils to values below pH 4.2 because SO_4^{2-} can be fixed in soils as aluminum hydroxosulfate (Schulze, 1989). Alternatively, mineral weathering may exceed the rate of anion leaching and no detectable change in exchangeable cations may occur for decades. Concomitant changes in forest condition (mortality or decreased growth) and changes in nutrient cycling should probably not be expected during the early phase of increased deposition. An early effect of increased S, N, and H deposition could be a fertilizer response due to greater availability of S, N, and basic cations in the soil. Some fertilizer response is suggested in the tree tissue chemistry data of both the Michigan gradient and the Pennsylvania gradient.

3.1.2 Trends Along Elevational Gradients of Cloud Deposition

In the spruce-fir forests in the Appalachian Mountains, patterns of soil chemistry may be examined to test the hypothesis that levels of soil exchangeable nutrients are related to patterns of atmospheric deposition. Although not directly measured on all mountains, atmospheric deposition of acidic compounds is reasoned to increase with elevation because the frequency of cloud events increases with elevation, and cloud water chemistry is more concentrated than other forms of precipitation (see Section 2.7).

Exchangeable nutrients are positively charged ions (cations) that are "held" electrostatically by the soil. Exchangeable cations are measured in the laboratory by replacement with another positively charged ion (typically NH_4^+). With the exception of nutrients dissolved in soil solution, exchangeable nutrients are the most easily "removed" from soil and are thought to represent what is readily available for root uptake. Elements (such as phosphorus (P) or Al and sometimes cations) may be referred to as extractable since stronger chemical analyses (e.g., dissolutions) are used to remove these elements from the soil in the laboratory.

In sampling soils along transects with increasing elevation in the northern Appalachians, decreases in exchangeable Ca (Ryan and Huntington, SF05-8; Huntington and Ryan, SF05-6; Johnson et al., SF08-4; see also McLaughlin et al., SF10-3 in Table 9) and exchangeable Mg (Johnson et al., SF08-4) have been observed. Exchangeable cations in the forest floor and the soil at two elevations on Mt. Moosilauke, NH, are shown in Figure 13. Increases in extractable P (Ryan and Huntington, SF05-8), extractable Al (Johnson et al., SF08-4), and exchangeable potassium (K) (Johnson et al., SF08-4) have also been observed. Exchangeable K concentrations did not always increase with elevation (Ryan and Huntington, SF05-8).

In contrast, no changes in extractable Al or in base saturation were observed with increasing elevation in the southern Appalachians (Wells et al., SF21-4). Wells et al. did observe decreases in exchangeable Mg and increases in exchangeable K, increases in extractable Pb, and increases in extractable SO_4^{2-} with increases in elevation.

Joslin et al. (SF27-1) observed higher concentrations of soil solution NO_3^- and soil solution Al at a site receiving higher cloud water inputs compared with a site with lower cloud water input at Whitetop Mountain, VA. These extremely high NO_3^- concentrations and similar patterns of high and low concentrations over a season between soil solution Al and NO_3^- at Whitetop are shown in Figure 14. Decreases in base saturation and increases in soil solution Al are the type of changes one would expect due to increasing soil solution acidity (Bohn et al., 1979). Increases in nitrification may be expected with increased deposition of NH_4-N. Strader et al. (SF17-1) reported high N contents in throughfall (18-32 kg/ha/yr with two-thirds as NH_4-N) and high soil N mineralization (26-180 kg/ha/yr) at elevations from 1579 to 2006 m in the southern Appalachians. Nitrate was the dominant anion in soil solution collected from a high (2006 m) and a low (1750 m) site in the Black Mountains of North Carolina (Smithson et al., SF12-7). Changes in solution Al, Ca, and Mg were highly correlated with changes in NO_3^- concentrations.

Wells et al. (SF21-4) found that extractable Pb was higher on west-facing slopes than on east-facing slopes in the southern Appalachian Mountains, but other soil properties did not vary according to exposure. No differences in soil chemical properties between east and west aspects were reported by Ryan and Huntington (SF05-8) for Mt. Moosilauke, NH. Lack of an influence of exposure on soil chemical properties suggests that deposition loadings do not vary with exposure in the high-elevation spruce-fir forests, even though it is assumed (but has not been demonstrated due to lack of data) that west-facing slopes of these mountains receive higher deposition loadings, especially in the northeastern United States.

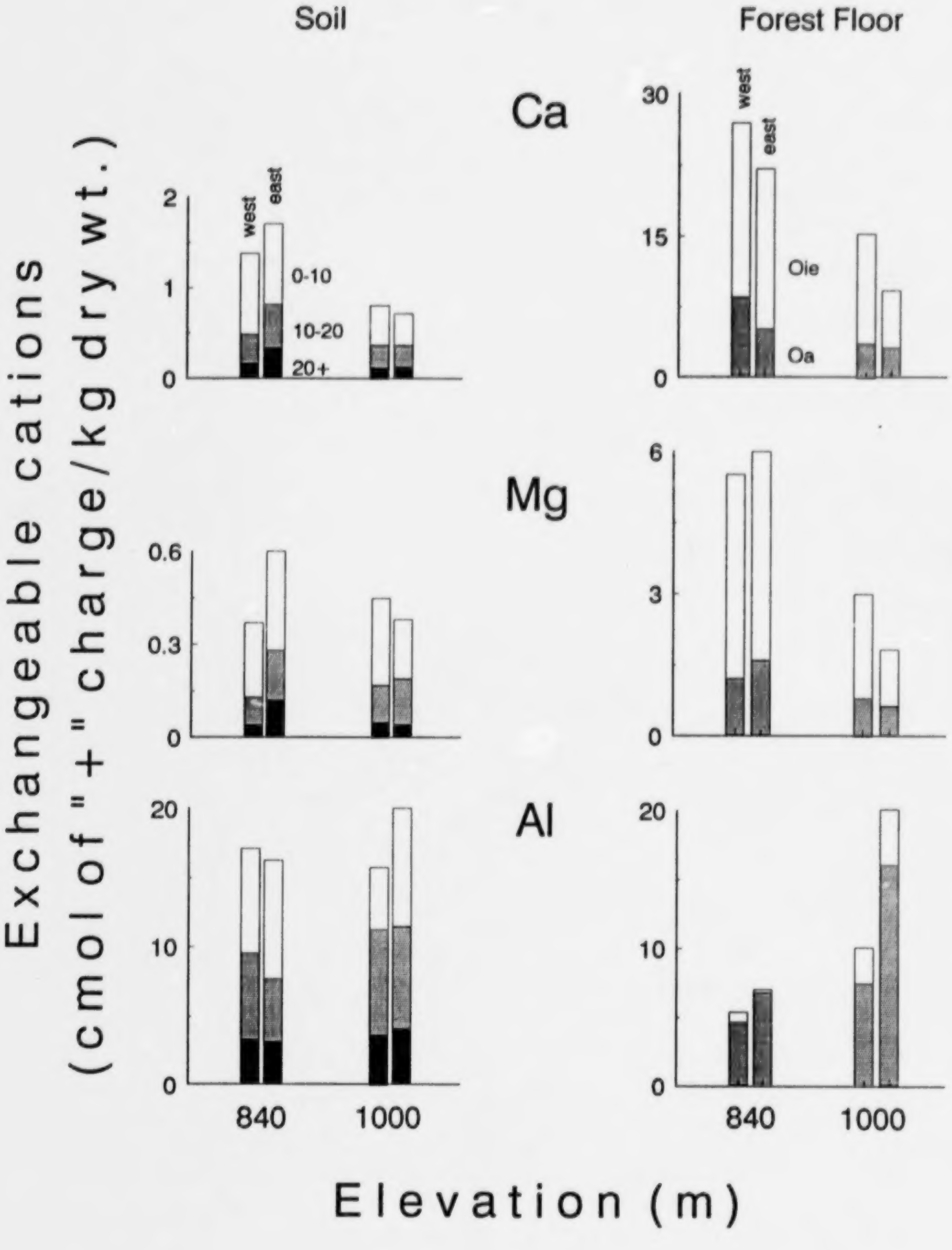


Figure 13. Exchangeable Ca, Mg, and Al (extracted in 1N NH_4Cl) in the Oie and Oa horizons of the forest floor and at three depths in the mineral soil. Spodosols at two elevations on east and west aspects of Mt. Moosilauke, NH, were sampled. Note varying scales of Y-axis (from Huntington and Ryan, SF05-6, and Ryan and Huntington, SF05-8).

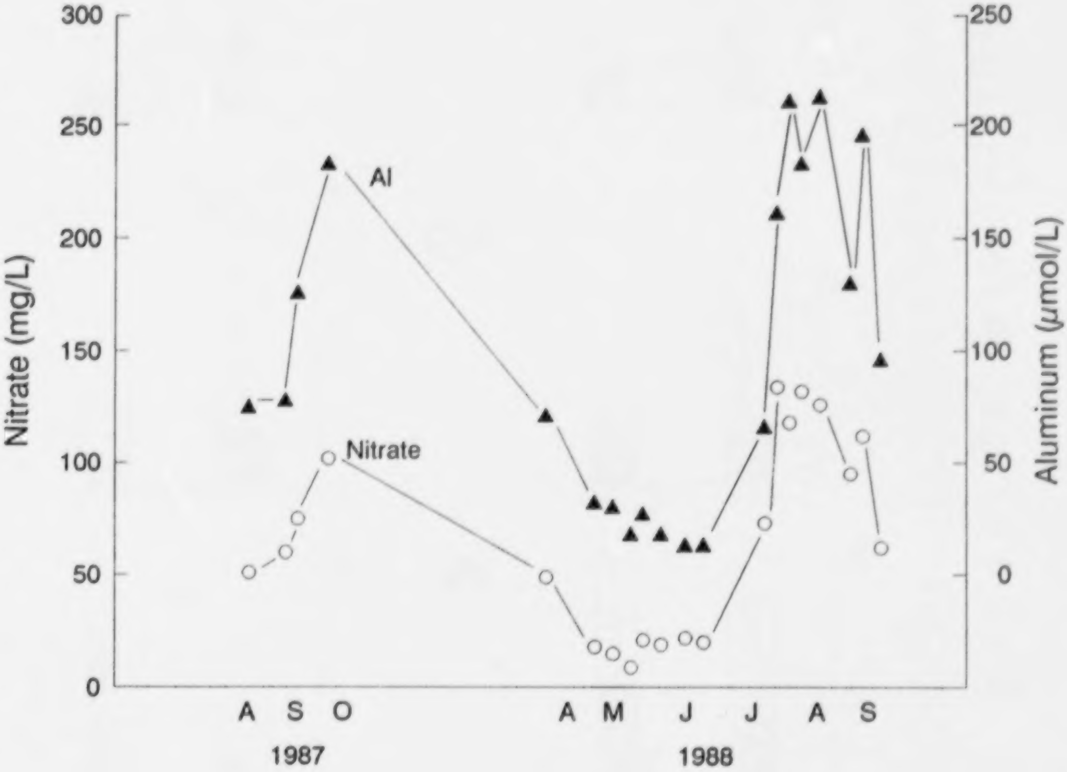


Figure 14. Seasonality in soil solution concentrations of Al and NO_3^- collected in tension lysimeters in A horizons at a site receiving high amounts of cloud deposition on Whitetop Mountain, VA. (from Joslin et al., SF27-1).

Failure to detect differences in soil chemical properties as a function of exposure or other topographic features may be due to the inherent variability of soils in forested ecosystems. Using a sampling area of only 12 x 14 m, Robarge and Smithson (SF12-2) have demonstrated that the within-plot variability for most soil chemical properties is greater than 30% when expressed as a coefficient of variation. Such inherent variability in soil chemical properties for forested soils limits the ability to detect statistically significant differences unless the experimental design includes a large number of plots and/or intensive sampling within plots (Robarge and Smithson, SF12-2). This variability may be further complicated by changes in soil type as a function of elevation or landscape position. Different soils may not respond to atmospheric deposition to the same extent. For example, Ryan and Huntington (SF05-8) concluded that Cryofolists, found at higher elevations on Mt. Moosilauke, NH, were more sensitive to further cation depletion than were the Spodosols at lower elevations.

In summary, these correlative trends of decreases in base cations and increases in Al with elevation demonstrate a fairly consistent relationship between soil chemical properties and atmospheric deposition of acidic compounds from clouds. However, the trends do not demonstrate that changes in soil chemistry were caused by atmospheric deposition. We do not have the historical data on soil chemical properties necessary for causal inference. In addition, other possible explanations for the observed trends exist, such as elevation differences in parent material, climate, mineral weathering patterns, vegetation, and land use history. In the southern Appalachians, site (i.e., mountain) had a greater effect on variation in soil chemical properties than did elevation (Wells et al., SF21-4; W. Robarge, personal communication).

3.1.3 Experimental Additions of Acidic Solutions to Soils

Soil chemical properties (e.g., complexation, ion exchange, dissolution and precipitation, and microbial processes) react relatively rapidly in response to changes in soil solution. Deposition of acidic compounds via rainfall and throughfall may cause short-term changes in soil solution composition as well as long-term changes in bulk soil chemical properties. Four FRP studies examined changes in soil chemistry as a function of artificial additions of acidic solutions to soils. Three studies are summarized in Table 5 and one seedling study from Table 4 is also discussed here. In addition, the ROPIS East project and the Watershed Manipulation Project (discussed later in this section) are examining changes in soil chemistry as a function of simulated acidic additions.

In controlled laboratory experiments, Smithson and Robarge (SF12-6) compared the effects on soil solution composition of simulated throughfall solutions (equal in composition to throughfall from a spruce-fir canopy at 2006 m elevation in the southern Appalachians) with distilled water (Figure 15). Increasing the acidity or ionic strength of the simulated throughfall resulted in increased Al concentration in soil solution, but the Al concentrations in extracts from Oa, A, or B horizons did not exceed 100 μM. Failure to obtain high concentrations of Al (i.e., 200 μM) with simulated throughfall agrees with the field measurements of soil solution composition obtained by Smithson et al. (SF12-7) using tension lysimeters. Concentrations of Al exceeding 200 μM were observed by Smithson et al. (SF12-7) in only approximately 1% of the 983 samples collected throughout the growing season in the Black Mountains, NC, and Whitetop Mountain, VA. The controlled experiments of Smithson and Robarge (SF12-6), however, were confounded by the production of relatively large amounts of NO_3^-, even when soil samples were stored at 4°C.

Huntington et al. (SF30-1) hydrologically isolated blocks of soil and added sulfuric acids of pH 3.5, 4.5, and 5.1 at Whiteface Mountain, NY. The isolation procedure cut live roots and caused increased production of NO_3^- in the soil solutions. In addition, concentrations of Al sampled in tension lysimeters were highly correlated with concentrations of NO_3^-. Concentrations above those thought to be toxic to red spruce roots (200 μM) were induced, but only with abnormally

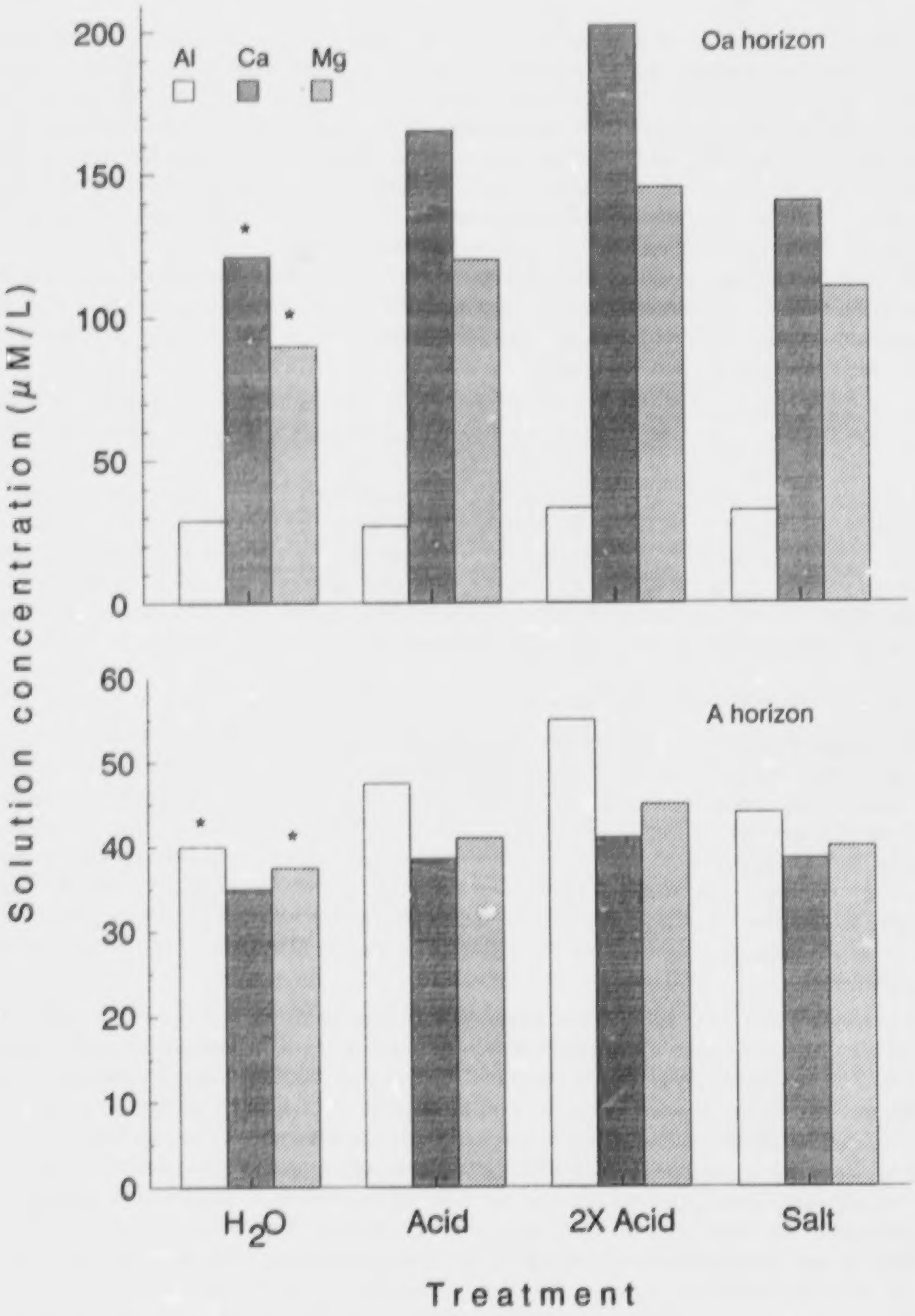


Figure 15. Solution Al, Ca, and Mg concentrations in pressure extracts of spruce-fir forests soils treated with water, acid, or salt solutions. Shown are Oa and A horizon samples collected at Smithson and Robarge's 1760-m site near Mt. Mitchell, NC. *Asterisks above each element in the H_2O treatment indicate statistical significance* ($p \leq 0.01$)(from Smithson and Robarge, SF12-6).

high NO_3^- in the soil solution that had itself been induced during the first year by the isolation procedure. Based on realistic NO_3^- concentrations, the authors concluded that roots were exposed to Al concentrations of 200 μM only in the forest floor and less than 1% of the time under ambient conditions. These conclusions agree with the observations of Smithson et al. (SF12-7) in the southern Appalachian Mountains. Research is continuing, and results from a second year should provide more definitive information as the disturbance effect is expected to subside.

Meier et al. (SF02-1)(Table 4) observed greater than 50% decreases in base saturation, exchangeable Ca, and exchangeable zinc (Zn) following simulated rains of pH 2.5 when compared with simulated rains of pH 5.5. They also observed decreases of up to 0.6 pH units in soil pH and greater than 20% increases in exchangeable acidity during the treatments. Changes in Mg, K, and P were not statistically significant. The treated soil was classified as a loamy-skeletal, mixed frigid, Typic Haplumbrept. It was collected at 1885 m from a red spruce stand on Mt. Mitchell, NC, that, according to Meier et al., showed "visual evidence of decline." The soil was exposed to simulated rains three times per week, either with or without red spruce seedlings planted in them. Compared with pH 5.5, statistically significant effects (decrease in base saturation, decrease in exchangeable Ca, decrease in exchangeable Zn, decrease in soil pH, and increase in exchangeable acidity) were observed after 25 applications at pH 2.5 ($p<0.05$). After 50 applications, some effects at pH 3.5 were significantly different from those at pH 5.5 (for soils without seedlings: increased exchangeable acidity and decreased base saturation; for soils with and soils without seedlings: decreased soil pH).

Ludovici et al. (SC05-8) observed about 10% decreases in base saturation, Ca concentration, and Mg concentration in soils following applications of simulated acid rains of pH 3.3 compared with simulated acid rains of pH 4.3. In addition, soil pH decreased from 4.57 to 4.49 and cation exchange capacity (CEC) increased from 3.00 to 3.39 cmol/kg. Ludovici et al. placed the top 10 cm of Helena sandy clay loams (clayey, mixed, thermic aquic Hapludult) into pots and planted them with loblolly pine seedlings. The soils and seedlings received fertilizer before treatments of simulated acid rain began. Rains of pH 3.3 and 4.3 (with varying S:N ratios) were applied three times per week for 20 weeks. Soil pH, base saturation, and Ca and Mg concentrations showed slightly greater reductions in soils receiving acid applications composed of sulfate compared with acids composed of nitrate. After 20 weeks, Ludovici et al. observed a 13% increase in fine root growth at pH 3.3 compared with pH 4.3.

Although not an experimental addition of acid, an experimentally induced change in cation availability in soils was examined by Binkley et al. (SC16-1) and is reviewed here. Binkley et al. observed decreases in soil pH of 0.3 to 0.8 units after 20 years following a conversion of a cotton field to a pine plantation. They also observed decreases in extractable cations and increases in Al. These changes were attributed to increased cation uptake and storage by the vegetation as hypothesized by Ulrich (1983) and Reuss and Johnson (1986).

In summary, these studies demonstrate changes in soil chemical properties due to additions of acids or change in some other component of the nutrient cycle. These results indicate that some soils may be less buffered against changes than is generally expected. However, the observed changes can be interpreted in different ways. It is uncertain what effects, if any, the increases in Al mobility or decreases in base cations would have on tree growth. Both Smithson and Robarge (SF12-6) and Huntington et al. (SF30-1) observed that most of their elevated Al concentrations were still below 200 μM, a threshold level of monomeric Al in soil solutions that has been observed to cause reduced root growth in red spruce in short-term seedling studies (Joslin and Wolfe, 1988). Growth of the seedlings was not reported by Meier (SF02-1), but Reinert (SC05-1, see Table 4) observed no growth reductions due to acidity on seedlings in a experiment similar to that of Ludovici (SC05-8). While no dramatic effects were observed on seedlings, it may be best to conclude that these results are short term and that effects on trees are still uncertain. Caution is also warranted since two studies mentioned that potential confounding of Al concentrations by high NO_3^- was caused by the experimental manipulations of the soils.

The observation of high NO_3^- in soil solutions of soil that was manipulated or disturbed during the collection procedure merits further discussion. These soils were from high-elevation spruce-fir forests. As discussed earlier, Joslin et al. (SF27-1) observed high solution NO_3^- in soils at Whitetop Mountain, VA. High rates of N inputs in throughfall and high rates of mineralization were observed at high-elevation sites on Mt. LeConte in the Great Smoky Mountains National Park and on Whiteface Mountain, NY, by Strader et al. (SF17-1) and on Mt. Mitchell, NC, Clingmans Dome in the Great Smoky Mountains National Park, and Whitetop Mountain, VA, by Sasser and Binkley (SF17-2). Increased Al in soil solutions is associated with high NO_3^- concentrations (Joslin et al., SF27-1) and with NO_3^- formation (Smithson and Robarge, SF12-6). The N cycle in these high-elevation forests may be enriched by high rates of atmospheric inputs of N and by a high potential for soil nitrification which in turn, appears to be linked to increased Al mobilization.

3.1.4 Literature Reviews and Modeling Projections

Literature reviews and modeling projections have indicated that atmospheric deposition can change soil chemical properties (Table 11). Binkley et al. (1989), in an analysis that included a literature review and computer simulations, concluded that half of southern forest ecosystems do not retain S inputs in the soil. Therefore, these ecosystems may be prone to SO_4^{2-} leaching of soil cations. Richter (SC99-19), in a review of soil solution chemistry and acidic deposition in southeastern forests, also speculated that acidic deposition may increase the distribution of polyvalent cations such as Al in soil solutions and result in greater leaching of nutrient cations. Additionally, atmospheric deposition is thought to be replenishing soil N lost due to past land use practices.

3.1.5 Tree Condition as a Function of Soil Chemistry

Four FRP studies examined red spruce crown condition as a function of soil chemical status (Table 5). Crown vigor was assessed as percent of recent needle loss from live crowns.

On Mt. Moosilauke, NH, Huntington et al. (SF05-7) observed lower concentrations of soil P and forest floor Mg and Ca at sites where red spruce showed declining crown condition. They also reported a positive correlation between soil and foliar Ca. Overall, the authors concluded that foliar nutrient concentrations were not related to crown condition and, in general, that red spruce do not appear to be deficient in foliar nutrients with the possible exception of P. They suggested that availability of nutrients, particularly Mg and P, may play a role in spruce vigor on Mt. Moosilauke, but there is no demonstration that nutrient stress causes reduced vigor.

On Whiteface Mountain, NY, Johnson et al. (SF08-3) detected no relationships between soil pH, soil cations, or soil Al and crown damage in red spruce. In another study, Johnson et al. (SF08-14) observed no correlation between soil and foliar levels of K, Ca, or Al, and no relationship between foliar Ca or Mg and crown condition, although decreases in foliar K were associated with declining crown condition. Johnson et al. (SF08-3) concluded that soil cations were generally not limiting, but that a potential for limitations of P and Mg exists.

Joslin et al. (SF27-1) observed decreased foliar growth of red spruce at a site on Whitetop Mountain, VA, that received higher cloud deposition of water, SO_4^{2-}, NO_3^-, and NH_4^+ compared with a site that received lower deposition of the same components. They also observed soil Al levels near levels reported to be toxic to roots and decreased foliar Mg, Zn, and Ca concentrations at the high-deposition site.

In summary, soil nutrient status does not appear to be related to loss of foliage in red spruce, particularly on Whiteface Mountain. Although red spruce crowns are reported to be in worse condition on Whiteface Mountain than on Mt. Moosilauke (Friedland, SF05-9; T. Huntington, personal communication), the soils at Whiteface Mountain have higher base saturations and higher concentrations of soil exchangeable Ca than the soils at Mt. Moosilauke (see Johnson et al., SF08-14, and Huntington and Ryan, SF05-6). These two observations (i.e., worse crowns but better soil nutrient status at Whiteface compared with Moosilauke) suggest that cation deficiency is not a primary cause of change in crown condition. However, on Whitetop Mountain, there is a correlative relationship between soil nutrient status and foliar condition: high soil Al levels, reduced foliar Mg, Ca, and Zn concentrations, and decreased foliar growth occur at a high-deposition site compared with a low-deposition site (Joslin et al., SF27-1). Cation deficiency should not be judged on the basis of these correlative studies alone.

3.1.6 Soil Studies of Other Programs

In this section, we compare soil studies of several concurrent programs with the FRP results discussed above. Special emphasis is placed on nutrient cycling since results discussed thus far demonstrate that atmospheric deposition of SO_4^{2-} and possibly NO_3^- alter nutrient cycling patterns. The FRP results by themselves are too incomplete to allow definitive conclusions. The results discussed here support many of the FRP results. Since these programs were not reviewed in the methods section, a brief description of each program is provided.

IFS Results

The Integrated Forest Study (IFS) has performed a substantial amount of research on atmospheric deposition and nutrient cycling. The IFS was funded primarily by the Electric Power Research Institute (EPRI) and also in part by the FRP, the Canadian Forest Service, and the Norwegian Forest Research Institute. Research was conducted at 17 forest sites in the United States, Canada, and Norway. These sites, which represent a range of climates, air qualities, soils, and vegetation, facilitate testing of hypotheses about the effects of atmospheric S and N deposition on forest nutrient cycling. Data were collected at 13 intensive measurement sites to estimate nutrient standing stocks in the vegetation, forest floor, and soil and to estimate fluxes between the atmosphere, canopy, and two soil depths. The following information is from the IFS Annual Report (Lindberg and Johnson, 1989).

Total atmospheric deposition of SO_4^{2-}-S across the 17 sites ranged from 10 to 42 kg/ha/yr, while N deposition ranged from 5 to 25 kg/ha/yr. The lowest deposition of both elements occurred in the northwestern United States and the highest occurred in the Great Smoky Mountains, the Piedmont, and at Whiteface Mountain, NY. Levels of S flux from a site generally corresponded to S input levels. Sites with low S inputs tended to retain S inputs. A surprising result was that a number of sites, especially those with high S input levels, exhibited net S losses (Figure 16). However, the amount of S loss relative to the amount of S input was relatively small. These net S losses could be due to underestimates of S inputs, overestimates of S losses, SO_4^{2-} desorption, and/or net S mineralization.

Annual gains or losses of N varied considerably across sites (measured as inputs versus outputs, as shown in Figure 17). High N losses were observed at some of the Great Smoky Mountain sites and the Turkey Lakes in Ontario, and, as expected, in the N-fixing red alder site in Washington. Overall, most sites appeared to be in steady state with regard to S leaching; that is, outputs were relatively similar to inputs. However, N appeared to be accumulating in most sites, and three sites appeared to be N-saturated (i.e., leaching NO_3^- in excess of inputs of total N). Saturation of N did not appear to be induced by deposition. The potential effects of N saturation include increases in soil acidity, soil solution ionic strength, soil solution Al activity, and decreases in soil base saturation (Cole and van Miegroet, 1989).

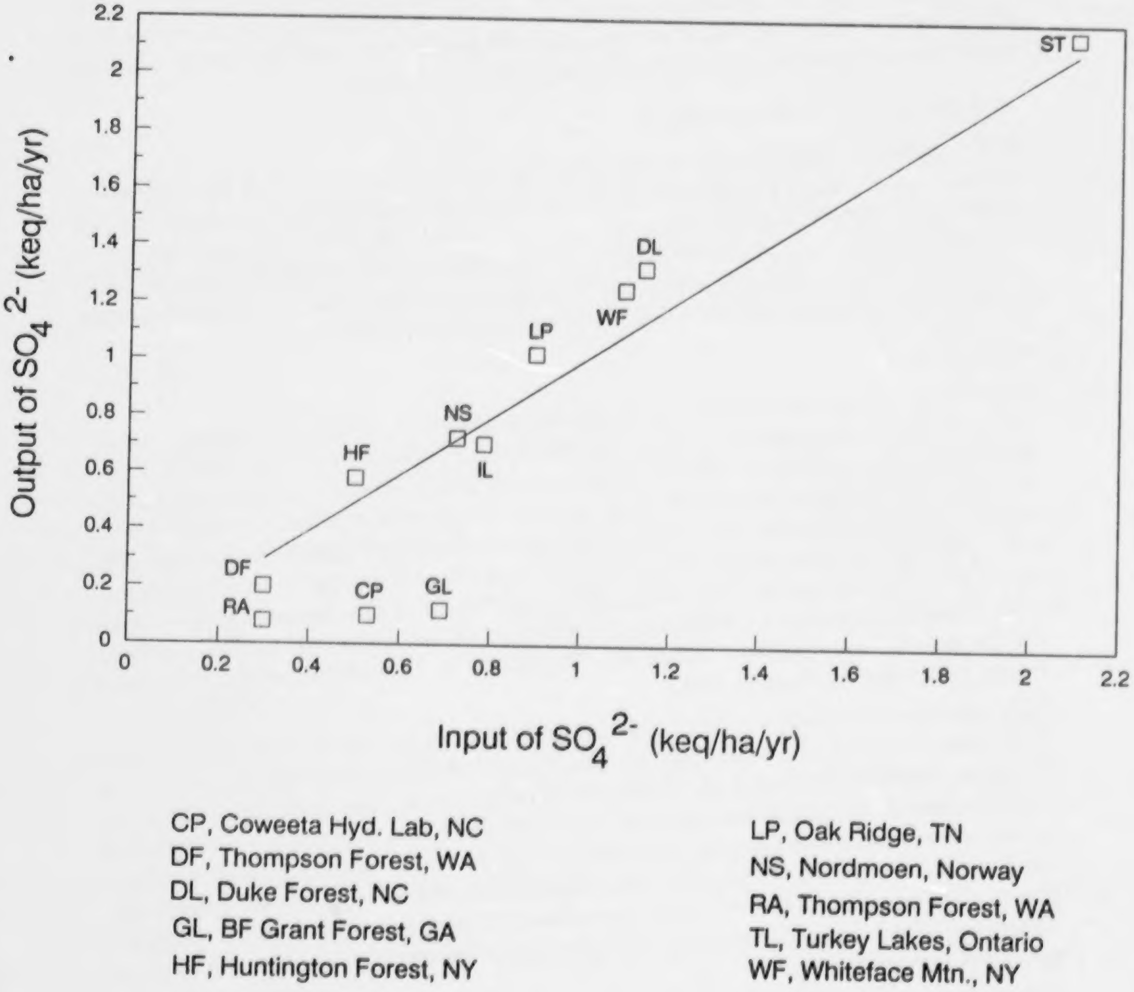


Figure 16. Sulfate outputs from B horizon as a function of SO_4^{2-} inputs in total (wet plus dry) deposition at IFS sites. Soil water flux was obtained from nearby gauged streams, modeling, Cl^- balance, or from evapotranspiration estimates. Diagonal line indicates equal inputs and outputs (from Mitchell, 1989).

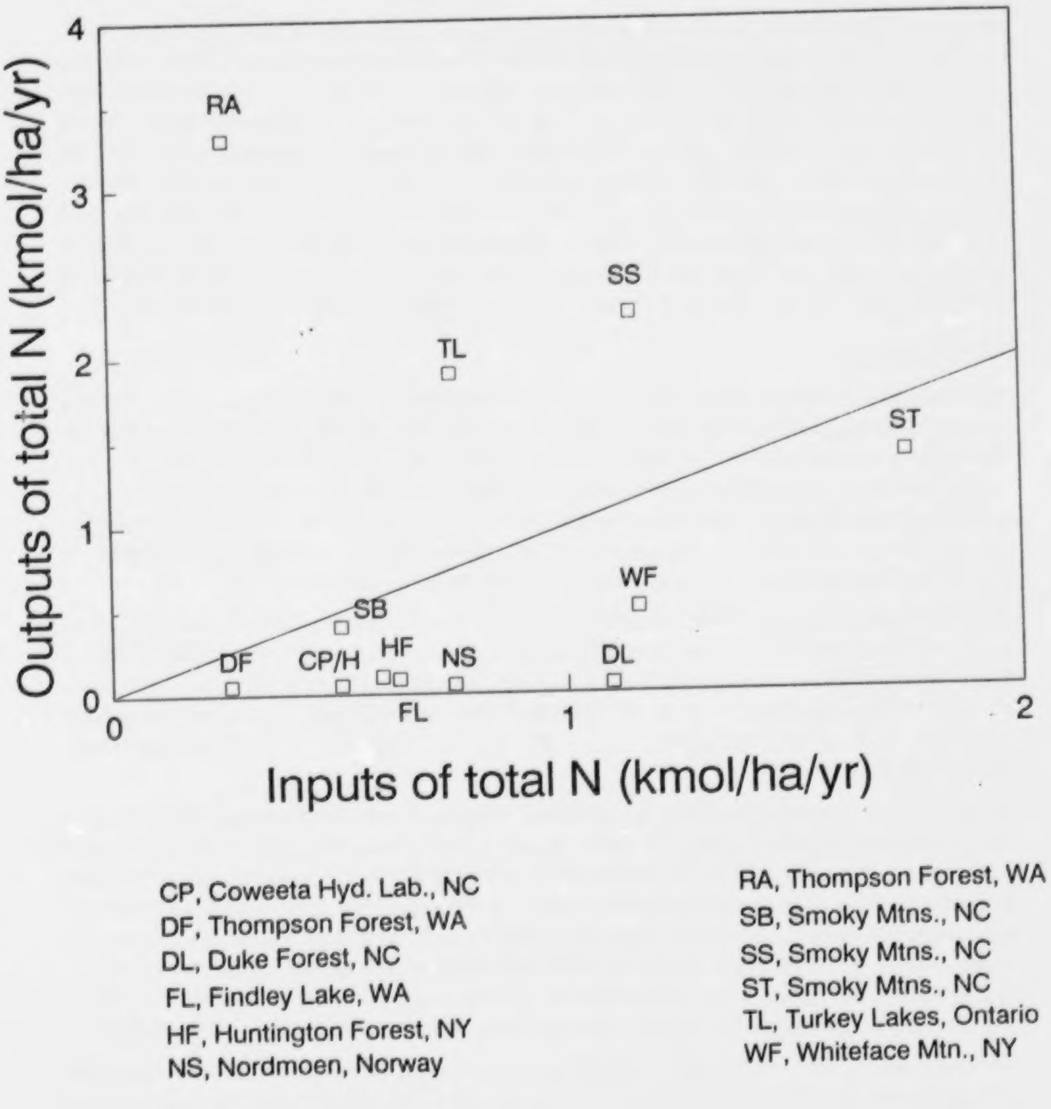


Figure 17. Total N outputs from B horizon as a function of total N deposition (wet plus dry) at IFS sites. Soil water flux was obtained as described for Figure 16. Diagnoal line indicates equal inputs and outputs (from Cole and Van Miegroet, 1989).

A principal objective of the IFS study was to determine the extent to which acidic deposition may be inducing cation losses and soil acidification. As in FRP results, high-elevation sites had lower soil base saturation (less than 10% in the B horizon). High-elevation/northern soils were more acidic than those of low-elevation/southern sites (base saturation ranged from 8% to 85% in the B horizon). Glaciated soils tended to have higher total cation contents due to greater weatherable minerals.

More than 75% of the IFS plots showed base cation losses (inputs minus outputs; range = +500 to -2800 eq/ha/yr). No particular regional patterns of cation loss were evident. Since pollutants are assumed to be regional in effect, pollutants may not be a primary factor in the cation loss. Greatest cation losses occurred in the red alder site and the Turkey Lakes site, both of which have high NO_3^- production in the soil. Calcium budgets (inputs minus outputs) were positive for about half the sites and negative for the remaining sites. The same was true for K, while Mg budgets were negative in 17 of 19 sites. Fourteen of 19 sites lost at least 1.5 kg/ha/yr of Mg. In 7 of 19 sites, this represented more than 5% of the soil exchangeable pool (Figure 18). Thus, there appears to be a potential for Mg deficiency in the near term (without substantial weathering resupply). Also, Al was released in greater amounts in high-elevation or high-acidity sites.

ALBIOS Results

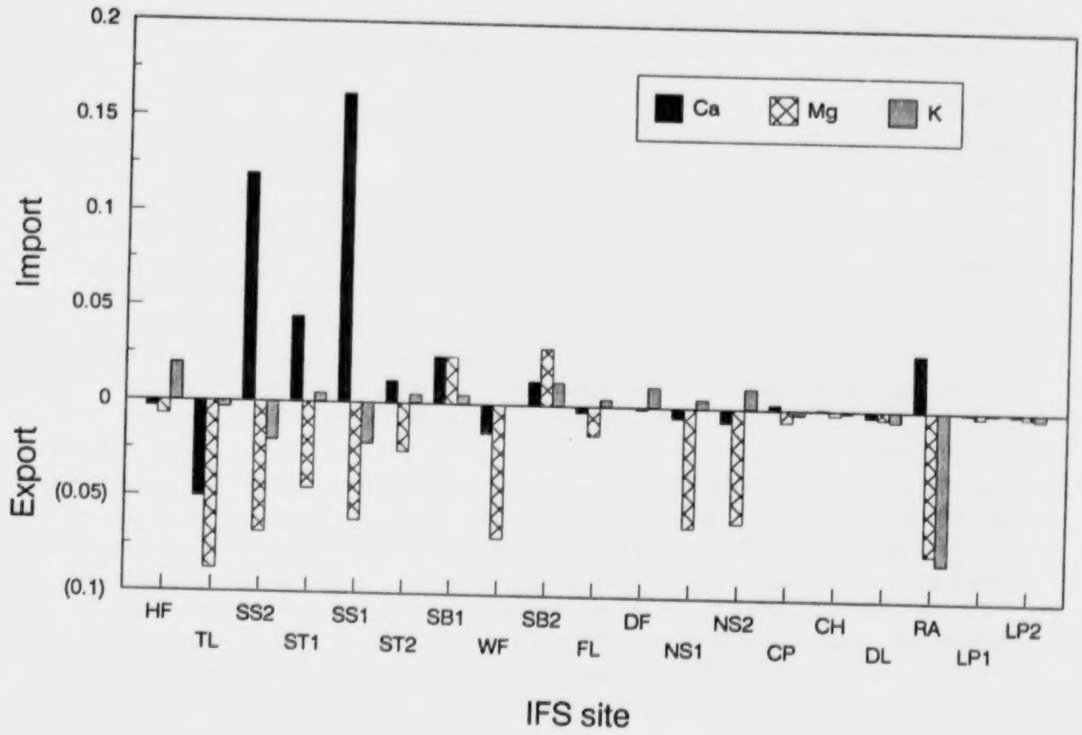
The Aluminum in the Biosphere (ALBIOS) project was initiated with EPRI funding to examine patterns of Al biogeochemistry and effects of Al on physiological processes of trees in eastern North America and northern Europe. The project focused on two hypotheses: 1) acidic deposition increases the concentrations and transport of soluble Al in soils and surface waters of forested watersheds; and 2) in sensitive ecosystems, acidic deposition may increase available Al to levels that are toxic to trees and aquatic biota, causing growth reductions, nutritional deficiencies, or mortality. The following is from a summary of ALBIOS by Cronan et al. (1989).

Field studies of Al biogeochemistry included 10 North American and four European watershed catchments that provided a broad range of contrasting forest types. Controlled studies included hydroponic systems, greenhouse soil culture experiments, and root ingrowth core experiments to evaluate potential toxicity of Al to an "indicator" tree species, honey locust, and to several commercial tree species: red spruce, sugar maple, red oak, American beech, European beech, and loblolly pine.

In the controlled studies, tree species exhibited a range of concentrations at which negative responses to Al occurred. Root and shoot growth of red spruce, European beech, and sugar maple were reduced by soluble Al concentrations of 200 to 800 μM; red spruce root growth was uniformly reduced at soil solution Al concentrations between 200 and 300 μM. In contrast, red oak, American beech, and loblolly pine tolerated up to 3000 μM of soluble Al. Elemental concentration of Al in plant tissues typically increased before growth reduction occurred. Additionally, these experiments indicated that apparent sensitivities of trees to Al in the rooting medium may be strongly influenced by ionic strengths of the culture solution or soil solution.

The comparative field results showed significant interregional differences in the concentrations of aqueous Al and strong acid anions in soil solutions at the North American and northern European study catchments. In general, the highest concentrations of soluble Al were found in the mineral soil horizons of the northern Spodosols and high-elevation southern Inceptisols in the United States, and the Inceptisols in Germany. These soils shared the following characteristics: base saturation usually less than 15%; pH in water less than 4.9; and soil solution SO_4^{2-} greater than 80 μM.

Cronan et al. (1989) speculated that the potential for Al toxicity probably varies across landscapes and may be most likely under the following conditions: in forests with trees shown to be sensitive from seedling studies (e.g., red spruce); forest ecosystems in which fine roots are concentrated



HF, Huntington Forest, NY
TL, Turkey Lakes, Ontario
SS, Smoky Mtns., NC
ST, Smoky Mtns., NC
SB, Smoky Mtns., NC
WF, Whiteface Mtn., NY
FL, Findley Lake, WA

CF, Thompson Forest, WA
NS, Nordmoen, Norway
CP, Coweeta Hyd. Lab., NC
CH, Coweeta Hyd. Lab., NC
DL, Duke Forest, NC
RA, Thompson Forest, WA
LP, Oak Ridge, TN

Figure 18. Fraction of soil exchangeable Ca, Mg, and K lost annually by leaching ([leaching - deposition]/exchangeable) at the IFS sites (from Johnson, 1989).

in mineral soil horizons with less than 10% to 15% base saturation; in northern and high-elevation southern ecosystems in the United States with large amounts of acidic deposition; in forests with marginal soil supplies of Ca, Mg or P; and in forests subject to drought stress and dependence on deep rooting for water supplies. Conditions for Al toxicity to some tree species appear to exist at some ALBIOS study watersheds. However, this conclusion is uncertain for several reasons: studies of Al toxicity were based primarily on seedlings; rooting media were artificial; chemical environments in roots have been in limited and manipulated ranges; experimental trees have generally not had mycorrhizae; and field soil solution chemistry may not reflect the soil solution chemistry in rhizospheres due to difficulties in sampling techniques.

DDRP Results

The Direct/Delayed Research Project (DDRP) is an EPA research program funded under NAPAP to predict the effects of acidic deposition on surface water chemistry (Church et al., 1989). The DDRP projects potential surface water chemistry changes as a function of varying S deposition scenarios in the northeastern United States and the Appalachian Mountains using the following: regional deposition chemistry and surface water chemistry data bases, a statistically rigorous watershed selection and extrapolation scheme, regionally extensive watershed mapping, soil sampling and analysis, and model simulation of watershed behavior. Because deposition chemistry is altered by soils as soil waters drain to surface waters, and because S retention by soil and leaching of base cations from soils influence whether surface waters in a watershed may acidify, much of the DDRP effort was directed towards evaluating regional soil conditions and projecting chemical responses.

A number of the DDRP findings pertain to soil chemistry and S deposition. Net watershed retention of atmospherically deposited S varied regionally. Approximately 75% of total S deposition was retained within the soils of the watersheds in the Southern Blue Ridge Province. From there, S retention generally decreased as one goes northeasterly; soil S pools in watersheds of the northeastern United States were approximately at steady state. Therefore, continued inputs via deposition are balanced by leaching. Leaching of SO_4^{2-}, the mobile S anion, carries base cations from the watershed to the surface waters. The importance of cation losses to forest condition depends on whether or not cation resupply through mineral weathering can match the losses.

Results of projections indicated that continued deposition at current rates could continue to mobilize Al and other elements in soils. This Al could be toxic to root systems. The importance of processes represented in the models used by the DDRP is being tested in field acidification experiments as part of the Watershed Manipulation Project (WMP). Whole watersheds are being treated with ammonium sulfate applications, and a series of soil chemical processes are being monitored.

ROPIS Results

The Response of Plants to Interactive Stresses (ROPIS) program has been sponsored by EPRI to examine the interactive effects of environment and air pollutants on tree growth, to determine the underlying physiological mechanisms of tree response, and to develop and test physiological and growth models to predict long-term responses of trees to the environment and air pollution. Specific regional hypotheses are being tested at three United States sites.

In ROPIS East, red spruce and sugar maple are under study at Boyce Thompson Institute at Cornell University, NY (Laurence et al., 1989). The red spruce research has two components: controlled exposures of seedling and sapling trees in open-top chambers and assessment of mature trees in the field. Red spruce saplings from a red spruce stand in Maine were dug out with their attached roots and soils and placed in large pots in open-top exposure chambers at the

Boyce Thompson site. The forest floor and soil A and B horizons were reconstructed in the pots and lysimeters were installed to sample soil solutions. Controlled exposure treatments consist of four levels of O_3 (charcoal-filtered, 1, 1.5, and 2 times ambient) alone and in combination with three levels of acidic precipitation (pH 5.1, 4.1, and 3.1). Seedlings and saplings have been studied for two years, and mature trees in the Maine stand have been studied for one year. Sugar maple exposures were planned for 1990, but results are not available yet.

After two years of exposure in the ROPIS East study (Laurence et al., 1989; Sherman and Fahey, 1989), the forest soil supporting red spruce saplings had significantly lower pH, significantly lower exchangeable Ca and Mg, significantly greater exchangeable Al, and higher rates of leaching of NO_3^- and cations as acidity of the simulated rain increased from pH 5.1 to 3.1. Most differences between the pH 5.1 and 4.1 treatments were statistically significant. In addition, pH treatments had significant effects on soil solution concentrations; greater soil solution concentrations of NO_3^-, SO_4^{2-}, Ca, Mg, manganese (Mn), and Al were observed with higher acidity treatments. Al toxicity was not expected due to relatively low Al:Ca ratios in the soil. In general, O_3 treatments did not affect concentrations of soil solutions.

In ROPIS South, loblolly pine are under study at Oak Ridge National Laboratory, TN, in cooperation with the Tennessee Valley Authority (TVA) (Kelly et al., 1989). This project has two components: a three-year (1986-1988) O_3 screening study and a three-year (1987-1989) factorial study of acidic precipitation, O_3, and soil Mg. During the screening study, five half-sibling families (one parent in common) were exposed to three levels of O_3 (from charcoal-filtered to ambient-plus-60 ppb). After one year of exposure, a family with an intermediate response was selected for the factorial study. Controlled exposure treatments consisted of three levels of O_3 (charcoal-filtered, ambient, and 2-times-ambient), two levels of acidic precipitation (pH 5.2 and 3.8), and two levels of Mg availability. In this study, Mg-deficient soil had no significant effect upon the seedling growth of loblolly pine after two years of applications of O_3, acidic precipitation, and soil Mg.

In ROPIS West, ponderosa pine are being studied at Whitaker's Forest, CA, near Sequoia National Park, in cooperation with University of California and the USFS (Temple, 1989). Controlled exposures of two-year-old ponderosa pine seedlings in open-top chambers began in 1988, using 1,400 seedlings from 19 half-sibling families and one full-sibling family (both parents in common). Controlled exposure treatments consist of three levels of O_3 (charcoal-filtered air, non-filtered, and non-filtered plus 150 ppb), three levels of acidic precipitation (pH 5.3 to 3.5), two levels of dry deposition (5% or 40% of ambient), and two levels of water availability (irrigated every 2 or 3-4 weeks). No results are available yet from this study.

3.1.7 Summary

Several observations support the hypothesis that chronic atmospheric deposition of acidic or acidifying compounds, such as H^+, SO_4^{2-}, NO_3^-, and NH_4^+, significantly alters soil chemical properties. Trends similar to those that would be expected due to soil acidification were observed along regional gradients of increasing SO_4^{2-} deposition and along gradients in the northern Appalachians where deposition of SO_4^{2-} is reasoned to increase due to increased cloud water deposition. These observed trends include increases in soil total S, increases in soil exchangeable Al, and decreases in soil exchangeable base cations (notably Ca and Mg). Soil solution Al^{3+} concentration is highly correlated with solution NO_3^- concentration, and it may be mobilized by NO_3^-. Changes in soil chemical properties can also result naturally from changes in vegetation and have been found to be highly variable on spatial scales as small as meters. Continued losses of soil Mg may be a future problem with high-elevation soils. However, data are generally lacking to link forest condition and deficient soil cations.

Soil chemical changes can be induced with artificial acidification. Modeling projections and literature reviews suggest that SO_4^{2-} deposition may eventually lead to increased cation leaching in the Southeast. The DDRP indicated that sites varied in their ability to retain atmospherically deposited SO_4^{2-}, and that sites in the Northeast are already saturated with respect to SO_4^{2-}. Most of the IFS sites were sustaining net losses of soil Mg; weathering resupply is still an unknown. The ALBIOS studies suggest that Al solubility increased with acidic deposition and that it may be contributing to tree stress in some sensitive sites.

3.2 Roots and Mycorrhizae

The effects of pollutants on roots and mycorrhizae have been examined directly via controlled exposure work with seedlings and indirectly through field surveys that correlate tree and root conditions. Table 4 summarizes the FRP seedling studies on roots and mycorrhizae.

3.2.1 FRP Seedling Studies

Effects of Acidity

In the 13 seedling studies that examined the effects of simulated acid precipitation on roots, results were highly variable. Miller et al. (WC09-1) found reduced root growth due to acidity for all species of western conifers except Engelmann spruce. In contrast, Hogsett and Tingey (WC08-1) observed mixed effects due to acidity, and Turner et al. (WC07-1) observed increased root growth in three of four western conifer species.

Of six studies evaluating the effect of simulated acid precipitation on red spruce roots, reduced growth of roots due to acidity was found in one study (Patton et al., SF07-1), and increased fine root branching, decreased coarse root growth, and decreased mycorrhizal infection were reported in another study (Deans et al., SF14-19). The remaining four studies reported no effect (Jacobson et al., SF06-1,2; Patton et al., SF07-2; Laurence et al., SF31-2; Thorton et al., SF27-3). No effects were observed on roots of Fraser fir (Seiler et al., SF13-1) or loblolly pine (McLaughlin et al., SC04-1; Reinert et al. SC05-1).

Dean and Johnson (SC13, personal communication) reported increases in root length density of slash pine exposed to increased acidity at a Gainesville, FL, site. The soils were sandy and low in nutrients, and the root increases may have been a response to the additional N in the acid treatments. Seedlings were grown in artificial potting media and not in naturally occurring soils in many studies (most laboratory studies and most of the field studies except those of the Southern Commercial Cooperative), and it is difficult to predict how increased acidity may interact with the exchangeable cations or act as a N fertilizer in these potting mixtures. The effects of acidity on soil nutrient cycling would occur relatively slowly, and effects may not become evident for several years.

One seedling study found no effect of acid on numbers of mycorrhizal root tips in red spruce grown in mixed soils collected from Mt. Mitchell, NC (Meier et al., SF02-1). However, there was an increase of the mycorrhizal species *Cenococcum geophilum* with increasing acidity. The acid applications resulted in decreased soil pH and base saturation, suggesting that a change in mycorrhizal-species associations may be induced by increased acidity.

The only meaningful conclusion at present is that there was no consistent direct effect of acidity on roots across these seedling studies. Moore (1974), in a review of acidity effects on roots, stated that often the effect of soil solution pH on roots is confounded with other chemical properties of the soil, such as the nutrient concentrations to which roots are exposed. Furthermore, the use of artificial potting media in these studies precludes assessment of the effects of simulated acidic deposition on roots due to soil changes.

Effects of Ozone

Thirteen seedling studies examined root growth (root length or mass increment) as a function of controlled exposures of O_3; seven of these studies observed some reduction in growth. All five loblolly pine studies showed negative effects due to O_3 (McLaughlin et al., SC04-1; Kress et al., SC06-3; Wiselogel, SC02-1,2; Reinert et al., SC05-1). Dean and Johnson (SC-13) found no effect on slash pine roots. One study reported reduced mycorrhizal colonization of roots of loblolly pine seedlings due to O_3 (McLaughlin et al., SC04-1).

All three red spruce studies reported no change in root growth due to O_3 (Alscher et al., SF16-5; Patton et al., SF07-2; Laurence et al., SF31-2). Laurence et al.'s (SF31-2) data indicated an 18.5% increase ($p = 0.11$) in root mass in their highest versus lowest O_3 levels (averaged over the three acid levels), which we reported as a significant effect in Table 4 due to our more liberal criteria. No effect of O_3 on roots was reported for Fraser fir (Tseng et al., SF13-2).

In other species, reduced root growth was observed for trembling aspen (Karnosky et al., EH03-5), Douglas-fir (Miller et al., WC09-1), ponderosa pine (Miller et al., WC09-1; Hogsett and Tingey, WC08-1), and lodgepole pine (Hogsett and Tingey, WC08-1). Generally, the remaining western conifers showed no consistent effects on roots due to O_3.

Effects of O_3 on root growth thus appear to be species specific. Loblolly pine appears to be sensitive, and red spruce appears to be tolerant.

3.2.2 FRP Mature Tree Studies

As was seen in seedlings, declining trees have been found to have declining root systems. Wargo et al. (SF15-1) studied trees showing 11% to 50% crown deterioration on Mt. Abraham, VT. They observed fewer live fine roots, fewer mycorrhizal tips, and fewer mycorrhizae types in red spruce with declining crowns than in trees with healthy crowns.

3.2.3 NCASI Results

In a study funded by NCASI, Sharpe et al. (1989) studied the effects of O_3 on C gain and allocation in loblolly pine seedlings using $^{11}CO_2$ tracers. Seedlings were exposed for 12 weeks to either 120 ppb of O_3 for 7 hrs, 5 days a week, or to charcoal-filtered air. Sharpe et al. reported that O_3 substantially reduced transport of photosynthate to roots of cottonwood and of loblolly pine seedlings.

In another study, four families of loblolly pine seedlings were exposed to one of six O_3 concentrations for 12 hrs, 7 days a week, during 3 consecutive growing seasons (NCASI, 1989). Ozone concentrations ranged from approximately 0.5 to 2.0 times ambient. After the first year, seedlings in each family showed visible injury. After two growing seasons of exposure, two families showed decreases in stem and branch dry weight when exposed to non-filtered air compared with seedlings exposed to charcoal-filtered air. The authors suggested that current ambient O_3 levels in the North Carolina Piedmont may suppress growth of some loblolly pine families.

3.2.4 ROPIS Results

In the ROPIS South study of O_3, acidic precipitation, and soil Mg (described in Section 3.1.6), root biomass, root length, and branching frequency of loblolly pine seedlings were not changed significantly after one growing season. In contrast, increasing acidic precipitation and soil Mg concentration resulted in a significantly greater number of mycorrhizal short roots, suggesting that mycorrhizal infection was more sensitive to these treatments than was seedling root growth.

In the ROPIS East study, the proportion of different red spruce mycorrhizal morphotypes counted in the Oa horizon changed significantly in response to O_3 alone, pH alone, and O_3 and pH in combination. The morphotypes are not taxonomically classed to species but simply as class

A, B, C, etc. Therefore, the only meaningful interpretation at present is that interactions of O_3 with morphotypes led to increases and decreases in both growth and frequency.

3.2.5 Summary

Short-term responses of seedling root growth to simulated acid precipitation were highly variable. Direct and consistent effects of acidity on growth or mortality of roots were not evident in these studies. However, indirect effects via changes to soil chemistry (S and N fertilization, loss of cations, and mobilization of Al) should not be discounted. Such changes will probably require several years of treatments because most soils are buffered against rapid changes in pH. The use of artificial potting media common in most of the seedling studies precludes assessment of the effects of simulated acidic deposition on roots due to soil changes.

Root growth of loblolly pine, trembling aspen, Douglas-fir, ponderosa pine, and lodgepole pine seedlings was reduced by O_3. A possible mechanism appears to be reduced C translocation to roots. Mycorrhizal frequency may be reduced and morphotype distributions may be altered by O_3; however, this work is still preliminary.

3.3 Altered Carbon Allocation

Carbon allocation includes components of photosynthesis and respiration as well as biomass allocation within the tree. The effects of atmospheric deposition on C allocation can be examined directly via seedling exposure studies and mature branch exposure studies, and indirectly via field surveys and measures on trees in environments with varying pollutant exposures. The special case of roots has been discussed above.

3.3.1 FRP Seedling Studies

The following discussion is derived primarily from the results in Table 4. The most recent findings of the Southern Commercial Forest Cooperative are summarized in Table 11.

Effects of Acidity

FRP studies have examined the effects of acidity on C allocation in seedlings by measuring photosynthesis, foliar mass and condition, and stem growth. In this section, we discuss each of these responses in turn.

Photosynthesis. Only data from loblolly pine and red spruce seedlings were available at the time of this summary. Of eight seedling studies that examined the effects of acidity on photosynthesis, none observed decreases in photosynthesis expressed on a leaf-area basis due to increased acidity. Four studies showed increases due to increasing acidity (Eamus and Fowler, SF14-9; Kohut et al., SF31-1; McLaughlin et al., SC04-1; Flagler, SC14), and four showed no effect (Richardson and Sasek, SC07-6; Chappelka et al., SC15-7; Seiler et al., SF13-1; Thornton et al., SF27-3). Of studies showing increased photosynthesis rates, progressive increases were observed at relatively low acid levels (pH 4.5 and 4.3)(McLaughlin et al., SC04-1, and Flagler et al., SC99-20).

Increases in photosynthesis due to acidity may be due to a fertilizer effect of N or other nutrients. Two of the studies reporting increased photosynthesis also measured growth responses. Kohut et al. (SF31-1) reported data that indicated increased growth due to increased acidity at the highest O_3 levels (2-times-ambient O_3); however, no growth trends due to acidity were apparent at lower O_3 levels. McLaughlin et al.'s (SC04-1) data indicated increased growth responses at moderate levels of acidity (pH 4.5 versus 5.2).

The increases in photosynthesis at higher acidities may also be related to changes in leaf chemistry or physiology. Jacobson et al. (SF06-1,2) showed that foliar N increased due to nitric acid application. Flagler (SC14) and Chappelka (SC15, cited in Flagler et al., SC99-20) observed no acid effect on chlorophyll content, while Reardon et al. (SC12, cited in Flagler et al., SC99-20) did observe increases in chlorophyll at pH 4.3 and 3.3 compared with pH 5.3. McLaughlin (SC04-1) observed no effect of acidity on stomatal conductance, but Eamus and Fowler (SF14-9) observed enhanced stomatal conductance and higher chlorophyll contents in green needles remaining on seedlings that had suffered foliar necrosis due to acidic mists of pH 2.5 versus pH 5.0.

Eamus and Fowler (SF14-9), when expressing their photosynthesis data on a chlorophyll-content basis instead of a leaf-area basis, observed decreased photosynthesis rates associated with increasing acidity. These observed decreases contrast with their observations of increasing photosynthesis due to acidity when photosynthesis was expressed on a leaf-area basis. Therefore, the measure of photosynthesis used should be considered when evaluating results.

Foliar mass and condition. Fourteen studies that reported data on the effects of acidity on foliar mass showed varied results. Simulated acid precipitation had mixed effects on loblolly pine foliage mass. Researchers found increases (Chappelka et al., SC15-1), decreases (Reardon et al., SC12-1), and no effect on foliage mass (McLaughlin et al., SC04-1; Kress et al., SC06-3; Reinert et al., SC05-1; Flagler et al., SC14). Red spruce showed either no effect of increased acidity (Laurence et al., SF31-2; Kohut et al., SF31-1; Patton et al., SF07-2), or decreases in foliage mass (Patton et al., SF07-1). Sulfuric acid of pH 2.5 increased red spruce needle abscission (Jacobson et al., SF06-1).

The effects of acidity on hardwoods varied across species. Black cherry (Davis and Skelly, EH01-1), white ash, yellow birch, and sugar maple (Jensen and Dochinger, EH06-1) had reduced foliage mass due to acidity. White oak, shagbark hickory, American beech, and European beech appeared to be insensitive (Jensen and Dochinger, EH06-1). Red maple and sweetgum appeared to have increased foliage mass due to acidity (Davis and Skelly, EH01-1).

Eleven seedling studies examined foliar condition (typically as discoloration) as a function of acidity; negative effects signify chlorosis and, in some cases, necrosis. Generally, negative effects on foliage condition occurred at or below pH 3.0. No study showed enhanced foliage conditions relative to control treatments. Hardwoods showed no negative effects of acidity on foliage condition (i.e., stipple, adaxial yellowing, necrosis, or fleck). Other responses appeared to be species specific. When comparing species common to different projects, foliage response to acidity appeared to be more consistent within a given species than were other responses, such as growth. Both Hogsett and Tingey (WC08-1) and Turner et al. (WC07-1) reported increased foliar injury for western red cedar and western hemlock, but Douglas-fir and ponderosa pine were not affected (injury was not specified, but all western conifer seedling studies considered banding, chlorotic mottle, tip necrosis, pigmented mottle, necrotic mottle, chlorosis, bud break, senescence, and abscission in their injury assessments). However, Miller et al. (WC09-1) observed increased foliar injury to Douglas-fir, ponderosa pine, white fir, and Engelmann spruce.

Red spruce foliage was sensitive in three studies where low pH levels (pH 2.5) were used (Leith et al., SF14-6; Chen and Wellburn, SF14-7; Jacobson et al., SF06-1,2), and insensitive in Patton et al.'s (SF07-2) study in which a higher pH level (pH 3.5) was used. Jacobson et al. (SF06-1,2) observed that acid-induced foliar injury to red spruce was significantly greater for sulfuric acids than for nitric acids. Two studies found that southern pine foliage was insensitive to solutions of pH 3.3 (Kress et al., SC06-3; Flagler, SC14).

Stem growth. Seventeen studies examined seedlings for various changes in growth of stems, total mass, stem diameter, or stem height as a function of acidity. A total of 24 species were tested under varying periods of growth and exposure conditions. Although responses were somewhat variable, most studies showed no effect on growth.

In seven studies with red spruce, one reported a decrease in stem growth, four reported no change, and two reported reduced stem growth due to acidity. These observations contrast with the observations of increased photosynthesis due to acidity for red spruce, since increased growth would be expected due to the increased rates of photosynthesis. Seiler et al.'s (SF13-1) data indicated reduced stem growth for Fraser fir.

The spruce and fir studies all used potted seedlings that should not have been nutrient deficient. Seedlings grown in artificial potting media may not be appropriate for growth response studies because one mechanism for changes in tree condition may be a fertilizer effect on nutrient-poor soils. Increased growth could occur with additions of acid in soils where N or S is limiting. Either increased stem growth or no effects were observed in the eight southern pine studies. The southern pine studies that reported increased stem growth used seedlings planted in natural soil (Kress, SC06-3; Dean and Johnson, SC13; Wright et al. and Chappelka et al., SC15-6,7), indicating a fertilizer effect.

Douglas-fir, western red cedar, and Engelmann spruce appeared to show some increased stem growth due to increased acidity, but the remaining western conifers appeared to be insensitive (Hogsett and Tingey, WC08-1; Miller et al., WC09-1). Black cherry (Davis and Skelly, EH01-1), white ash, and sugar maple (Jensen and Dochinger, EH06-1) showed reduced stem growth due to acid. Yellow birch and sweetgum showed increased stem growth (Jensen and Dochinger, EH06-1). Other hardwood species showed no changes in stem growth response to pH 3.0 versus 4.2.

Variability. Seedling response to acidity was highly variable across both studies and species. Sources of variation not under experimental control, or at least not available to be evaluated in this document, include: stage of phenological development; degree of environmental stress (i.e., moisture, temperature, nutrient, and light); length of treatment exposures; level of treatment (mean and extremes); length of time between treatment and assessment; rooting medium and size of pots (if used); degree of mycorrhizal infection; and genetic family (in the case of species that have wide range of occurrence or have been hybridized, such as loblolly pine). Shafer et al. (1989) examined the variation in response of loblolly pines from the seedling projects in the Southern Commercial Research Cooperative. Specific genetic families were chosen on the basis of geographic range, availability of a large number of seeds, and information about O_3 sensitivity. Shafer et al. reported substantial variation in growth response of loblolly pine seedlings across the projects examined, particularly in the response to O_3 between field and laboratory studies and among laboratory studies conducted at different sites. However, when Shafer et al. examined responses from one laboratory project that used continuously stirred tank reactors (which afford the greatest amount of environmental control), responses were typically repeated in the two years the same experiment was performed. From these findings, seedling response is expected to be somewhat predictable within a species, but the exact response depends on a number of factors other than treatment levels.

Effects of Ozone

As was found for acidity, the effects of O_3 on C allocation in seedlings have been measured on photosynthesis, foliar mass and condition, and stem growth. In this section, we discuss each of these responses.

Photosynthesis. Seven of 10 studies demonstrated some suppression of net photosynthesis due to increasing O_3 concentration. All five loblolly pine studies reported decreased photosynthesis due to O_3 (McLaughlin et al., SC04-1; Kress et al., SC06-3; Richardson and Sasek, SC07-6; Wiselogel et al., SC02-1; Chappelka et al., SC15-7). Preliminary results from these studies suggest that reductions in photosynthesis often were progressively greater with increasing concentrations of O_3, and ambient concentrations reduced photosynthesis when compared with below-ambient concentrations. Reductions in photosynthesis of southern pines due to ambient O_3 were more apparent in recent studies by Flagler et al. (SC99-20).

Shortleaf pine photosynthesis was also sensitive to O_3 (Flagler, SC14). White oak (Foster et al., EH06-2) and red spruce appeared less sensitive than other species. Although by our criteria we report a trend of declining photosynthesis due to O_3 in Laurence et al.'s (SF31-2) red spruce data and in Tseng et al.'s (SF13-2) Fraser fir data, in neither study was the effect statistically significant. Tseng et al. (SF13-2) reported large photosynthesis suppressions (over 40%) due to O_3. Kohut et al.'s (SC31-1) data, which were results from the second year of exposures of the same seedlings used by Laurence et al. (SF31-2), did not demonstrate a suppression of photosynthesis with increasing O_3. Furthermore, Thornton et al. (SF27-3) did not detect an O_3 effect on photosynthesis of red spruce seedlings exposed to ambient levels on top of Whitetop Mountain, VA. Therefore, with respect to photosynthesis, red spruce and white oak seedlings appear to be tolerant to O_3, but southern pines appear to be sensitive.

Foliar mass and condition. In the 15 seedling studies that examined foliage mass as a function of O_3, no increases in foliage mass were reported. Douglas-fir, ponderosa pine, lodgepole pine, western hemlock, and western red cedar were exposed to O_3 by Hogsett and Tingey (WC08-1), and all five of these western conifer species appeared to be sensitive to O_3. Decreased bud elongation and decreased needle dry weight were commonly observed. Six of eight loblolly pine studies reported reduced foliar growth, increased foliar chlorosis, or increased needle loss (Reinert et al., SC05-1,5; Kress et al., SC06-3; Reardon et al., SC12-1; Wiselogel et al., SC02-2; Wright et al., SC15-6). Wright et al. (SC15-6) demonstrated that sensitivity of loblolly pine also depended on genetic family. All three red spruce studies reported no effects of O_3 on foliage mass (Patton et al., SF07-2; Laurence et al., SF31-2; Kohut et al., SF31-1). Hardwood response varied by species. Species that appeared to be sensitive under these exposure regimes included white ash, yellow birch, sugar maple, red maple, black cherry, and white oak (Jensen and Dochinger, EH06-1; Davis and Skelly, EH01-1).

Eleven of the 13 seedling studies that examined foliage condition as a function of O_3 reported negative effects (e.g., increases in chlorosis, necrosis, or loss of foliage). Sensitive western conifer species included ponderosa pine (Hogsett and Tingey, WC08-1), white fir, and subalpine fir (Miller et al., WC09-1). Only one of three red spruce studies reported negative effects: Fincher et al. (SF16-4) found increased mesophyll cell damage. Both loblolly pine studies reported increased needle abscission, increased banding, and chlorosis (Kress et al., SC06-3; Wiselogel et al., SC02-1,2). Increased banding, chlorosis, and necrosis to foliage were also reported for slash pine (Flagler, SC14). As can be seen in Table 4, every hardwood species except red oak was sensitive (i.e., showed some combination of increased fleck, stipple, adaxial yellowing, or necrosis) in Davis and Skelly's (EH01-1) study, and half the hardwood species showed increased fleck in Jensen and Dochinger's (EH06-1) study. More recent data from open-top chambers show that foliar stippling of black cherry and yellow-poplar seedlings was significantly reduced by filtering O_3 from ambient air at sites in Pennsylvania (Skelly et al., EH04-4).

Stem growth. Of 21 seedling studies that examined changes in stem mass, total mass, stem diameter, or stem height as a function of increasing O_3, 12 showed reductions in at least one growth measure. Western conifer species showing decreases in these measures included ponderosa pine and western hemlock (Hogsett and Tingey, WC08-1), and possibly Douglas-fir (Miller et al., WC09-1). White fir and Engelmann spruce showed some increased growth due to O_3 (Miller et al., WC09-1). Stem growth of red spruce and Fraser fir appeared to be generally insensitive to O_3 (Tseng et al., SF13-2).

Seven of eight loblolly pine studies reported reduced stem growth due to O_3 (McLaughlin et al., SC04-1 lab; Reinert et al., SC05-1,5; Kress et al., SC06-3; Wiselogel et al., SC02-1,2; Wright et al., SC15-6). Shortleaf pine was showed no response to O_3 (Flagler, SC14), but slash pine stem growth was reduced (Dean and Johnson, SC13). As can be seen in Table 4, half of the hardwood species showed reduced growth due to O_3. Variability in seedling stem growth as a function of O_3 appears to be primarily a function of species. Of species that responded similarly in at least two studies, red spruce, sweetgum, and yellow-poplar showed no growth response, and loblolly pine, ponderosa pine, and yellow birch showed decreased growth (Jensen and Dochinger, EH06-1; Davis and Skelly, EH01-1; Karnosky et al., EH03-5). In open-top chambers in Pennsylvania, Skelly et al. (EH04-4) observed increased stem diameter growth and increased height growth of black cherry and possibly yellow-poplar seedlings when O_3 was filtered from ambient air. The differences were apparent in 1988, a year with high levels of O_3, but they were not evident in 1989, a year with lower O_3 levels.

Variability. In general, seedling response to O_3 appeared to be much less variable than responses to acidity. Seedlings showed increases in growth or photosynthesis in response to O_3 much less frequently than they did to acidity. Although response to O_3 appeared to be species specific, studies using the same species typically reported results that agreed qualitatively (i.e., in the direction of response). The same is not true for seedling response to acidity. The quantitative seedling response to O_3 appears to be fairly complex. For example, responses of loblolly pine vary as a function of genetic family. The effects of O_3 may interact with age of needles, and effects may carry over from the previous year (Flagler et al., SC99-20). Kress et al. (SC06)(reviewed in Flagler et al., SC99-20) observed a nearly linear effect of O_3 on photosynthesis, needle length, and needle number on first flush foliage. The second flush foliage shows no impact of O_3 except in the 3-times-ambient treatment. However, the third and fourth flush needles are 127% longer and photosynthesize at a higher rate (36%) when high-O_3 treatments are compared with ambient treatments.

Acidity and O_3 did not interact to any great degree, and any reported interactions were neither consistent nor easily interpretable. Compared with acidity, O_3 may act more directly on seedlings (e.g., on leaf condition, photosynthesis, and growth) or have more acute effects (e.g., on membranes of leaves). Acidity may act through more indirect mechanisms (e.g., winter injury or soil chemistry) and may interact with other variables (temperature or nutrient availability) to a greater degree than O_3 does. Thus, research on acidity may require longer study intervals to test for effects than O_3 studies require.

3.3.2 FRP Mature Tree and Sapling Field Studies

Five FRP studies described in this section present some physiology or growth data of sapling and mature trees from sites receiving differing amounts of acidic deposition.

McLaughlin et al. (SF10-3)(Table 9) compared red spruce saplings 1.5 to 2.5 m in height growing at an elevation of 1935 m with saplings growing at 1720 m on Clingmans Dome in the Southern Appalachians. They reported reduced photosynthesis and growth at low light levels and increased respiration. Although McLaughlin et al. did not present data to show that greater deposition of acidity occurs at the higher site, this is probably a reasonable assumption since the higher site receives 30% more precipitation. In addition, an increase in the Al:Ca ratio in soils and foliage was observed at the higher site.

Amundson et al. (SF31-3)(Table 9) examined the time course of needle physiology and chemistry of red spruce in three naturally regenerated stands, one at Whiteface Mountain, NY, and two at low-elevation sites in Maine (the latter do not receive cloud water deposition). The authors reported lower rates of net photosynthesis, lower sugar contents, earlier starch depletion, and lower C assimilated per unit of foliar N at Whiteface Mountain, and they concluded that these trees have a reduced capacity to assimilate C compared with red spruce at the two sites in Maine. Amundson et al. also observed higher foliar N but lower foliar P, Ca, and Mg at Whiteface Mountain than at the Maine sites.

Joslin et al. (SF27-1)(Table 5) studied mature red spruce trees at a site near the summit of Whitetop Mountain, VA, that, because of wind and topographic conditions, received 15% more SO_4^{2-} and 29% more NO_3^- than another nearby site. The site with greater deposition showed decreased foliar growth, decreased needle retention, and reduced foliar nutrient levels of Mg, Zn, and Ca. Like McLaughlin et al. (SF10-3), Joslin et al. reported increased soil Al (up to 200 M) levels at the high-deposition site.

Pregitzer et al. (EH03-4)(Table 5)and Witter (EH03-2)(Table 7) evaluated sugar maple stands along a gradient of increasing acidic deposition from Minnesota to Michigan. They reported no changes in growth along the gradient, but they found increases in the amount of cycled N and S in litterfall and throughfall as well as increases in cation fluxes in throughfall along the gradient.

Loucks at al. (EH05-8)(Table 7) observed no trend in mortality rates of hardwood trees greater than 20 cm in diameter along a deposition gradient from Arkansas to Ohio. However, along the whole gradient, they observed increased mortality from 1978 to 1987 when compared with rates from 1968 to 1977. Loucks et al. did not use direct measures of tree death, but rather they estimated year of tree death using criteria such as condition of the remaining tree, cross-dating of wood cores, or aging saplings that were released by the tree's death. These results are still preliminary.

3.3.3 FRP Branch Exposure Studies

Branch exposure chambers (BECs) are a method for assessing mature tree response to air pollutants. Branches of mature trees growing in the field are contained inside chambers in which the ambient air can be controlled. Either pollutants can be removed via filters or pollutants can be added to obtain higher than ambient concentrations. The reliability of data from BEC studies depends on the degree to which a branch is autonomous in meeting its C requirements. With respect to C translocation, preliminary results of fall $^{14}CO_2$ pulse-trace experiments indicated a high degree of autonomy of mature branches of ponderosa pine growing under uncontrolled field exposure conditions (Houpis and Cowles, WC20-1). After eight days of potential C translocation, less than 1% of the labeled C was found in needles, buds, or stems of the three branch whorls closest to the labeling point. Thus, since branches appear to be autonomous with respect to C movement, BECs should be appropriate for study of some aboveground air pollution effects, at least for mature ponderosa pine.

The BECs can be used as a cuvette to measure CO_2 uptake of whole branches. Houpis and Cowles (WC20-1) enclosed the foliage of a 5-yr-old potted ponderosa pine sapling in a BEC, and continuously monitored CO_2 uptake for three months. Figure 19 shows a typical diurnal trend in CO_2 uptake and illustrates variation due to light and temperatures inside the BEC.

Effects of Acidity

Vann et al. (SF34-1) used BECs to expose branches of four mature red spruce to treatments in the summer of 1988. Treatments were: 1) ambient gases and cloud water, with a chamber (control treatment); 2) ambient gases and cloud water, without a chamber (open treatment); 3) ambient gases with cloud water excluded (dry treatment); 4) charcoal-filtered air with cloud water excluded (filtered treatment); 5) charcoal-filtered air with cloud water excluded and deionized water added as mist (misted treatment)(see Table 9). Foliar samples collected at the end of treatments showed significant treatment effects: misted branches had the highest concentrations of total chlorophyll and carotenoids, and open branches had the lowest ($p = 0.01$). Cuticle thickness measurements followed a similar trend (Berlyn, 1989).

These data suggest that the measured foliar characteristics improved when ambient cloud water was excluded and that foliar characteristics were best when exposed to deionized mist compared with other treatments. Furthermore, treatments appeared to affect the degree of winter injury

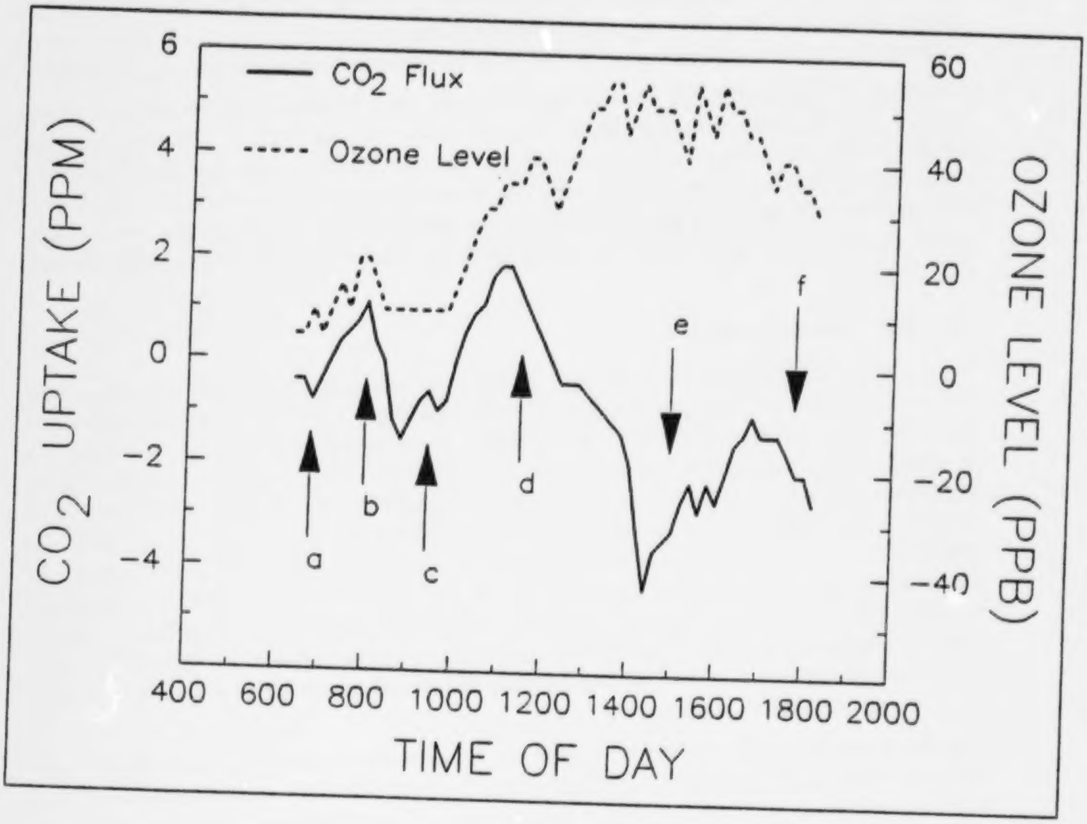


Figure 19. A diurnal patter of CO_2 uptake and O_3 concentration inside a branch exposure chamber on ponderosa pine. The midday depression in CO_2 uptake is due to high temperatures (38°C). Key: a, increasing CO_2 uptake and light intensity, sunrise; b, shaded by adjacent building; c, light intensity increased; d, peak CO_2 uptake; e, late-afternoon recovery; f, decreasing CO_2 uptake and light intensity at sunset (from Houpis and Cowles, WC20-1).

incurred during the following winter. Foliage from "clean" treatments (filtered, misted, and dry) had significantly less winter injury than foliage exposed to ambient cloud water (control and open; $p = 0.10$). The levels of winter injury in dry treatment and the filtered treatment were between the clean treatment and the control treatment (Figure 20). Degree of winter injury, however, was not significantly correlated with the cuticle and wax data of Berlyn (1989); the best correlation was with total cuticular layer ($r = -0.59; p < 0.10$).

Effects of Ozone

Wiselogel (SC18-3) found that photosynthesis was lower for sapling loblolly pine branches exposed to 2.5-times-ambient O_3 than for those exposed to ambient O_3 or to charcoal-filtered air. Figure 21a illustrates typical daily patterns of photosynthesis by O_3 treatment and in relation to light. Figure 21b shows differences in light intensity from ambient among chambers due to both the chamber skin and shading. In addition, although the chambers tracked ambient light similarly, light intensity varied up to 20% among chambers on the same tree. Differences in light intensity among chambers may complicate interpretation of results because light may influence the rate of photosynthesis irrespective of O_3 treatment, especially if light levels are below saturation (photon flux density $1400 \mu mol/m^2/s$; Teskey et al., 1986). In turn, the rate of photosynthesis may also affect the rate of O_3 uptake and thus the level of O_3 stress.

In contrast to Wiselogel's (SC18-3) results for photosynthesis, Vann et al. (SF34-2) found that the concentration of total chlorophyll and carotenoids in the foliage of mature red spruce trees was not significantly different between branches exposed to ambient versus charcoal-filtered air.

3.3.4 ROPIS Results

In the ROPIS South study, five half-sibling loblolly pine families were exposed to O_3 for three growing seasons. After the first growing season, seedlings grown with ambient-plus-60 ppb O_3 showed decreases in stem and root biomass compared with seedlings receiving ambient or charcoal-filtered air, and there was a significant family x O_3 interaction. During the second and third growing seasons, only family differences were statistically significant. In harvesting at the end of the second growing season, seedlings grown with ambient-plus-60 ppb O_3 showed significant decreases in stem and root biomass. After the third growing season, there were consistent, but not statistically significant, decreases in all but stem biomass measures for seedlings grown under ambient-plus-60 ppb O_3. Similarly, loblolly pine seedlings exposed to 2-times-ambient O_3 had a 13%-18% reduction in biomass compared with seedlings in charcoal-filtered air after two years.

No statistically significant growth responses to acidity were observed in loblolly pine seedlings in the ROPIS South study. In addition, rainfall chemistry had no significant effect upon either the visible coloration or the pigment concentrations of needles. However, results indicated significantly less chlorophyll a (7%), chlorophyll b (10%), and carotenoids (3%) in second-year needles of seedlings growing in the Mg-deficient soil compared with seedlings in a high-Mg soil.

In the ROPIS West study, one year of O_3 and simulated acid precipitation exposures equal to levels currently observed in the southern Sierra Nevada Mountains did not significantly affect the growth of ponderosa pine seedlings. Elevated O_3 did cause visible injury symptoms on ponderosa pine foliage, showing the susceptibility of this species to O_3 and suggesting that tree growth effects may be found in subsequent years of this experiment. No visible effects of acidity were observed.

In the ROPIS East study, red spruce saplings had significantly lower rates of net photosynthesis, as estimated from whole-tree CO_2 uptake and total foliage mass after two years of exposure to O_3. These results are considered preliminary because photosynthesis rates were calculated based on estimated needle mass. Photosynthesis rates will be recalculated when the saplings are harvested, and needle mass will be measured at the end of the experiment. In the first year of

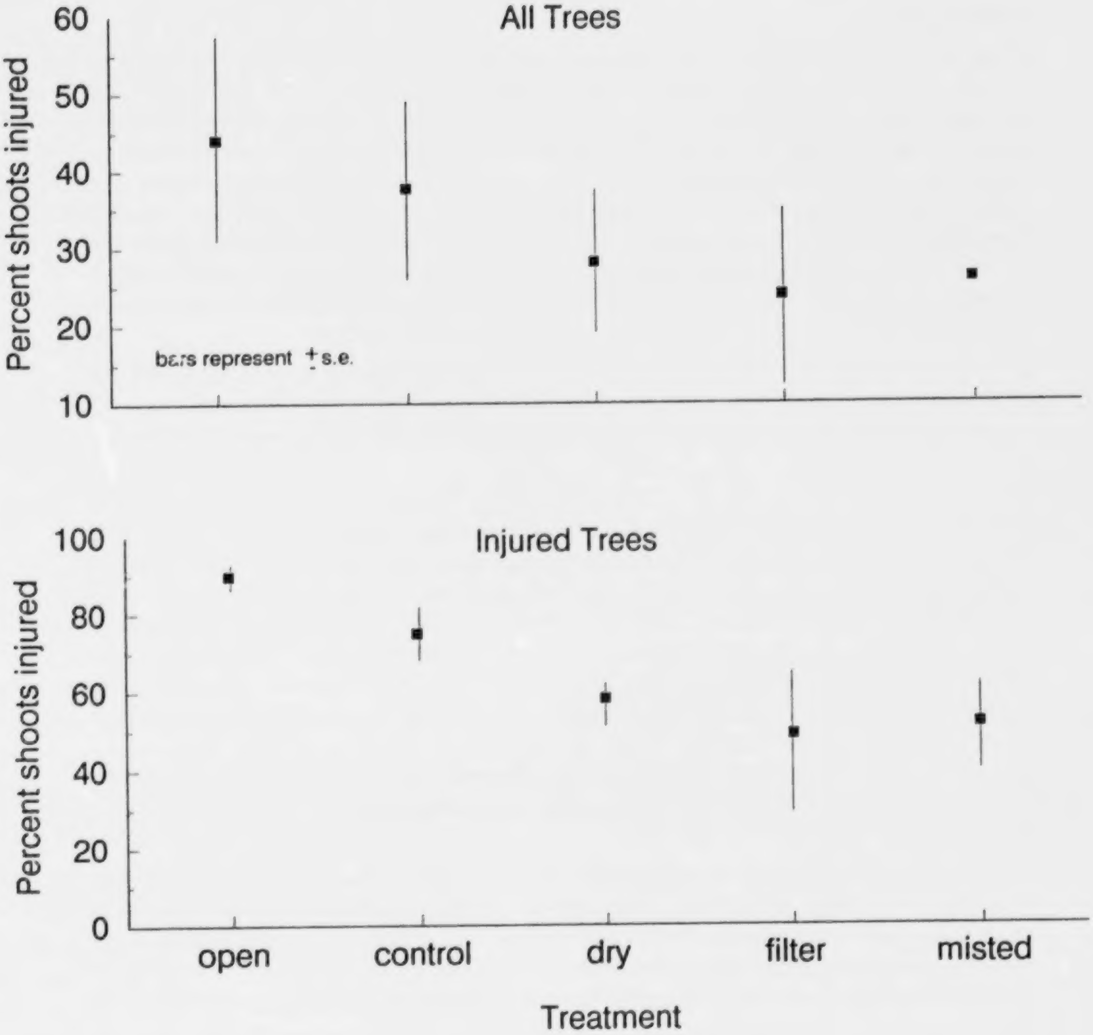


Figure 20. Winter injury to foliage on branches of red spruce trees as a function of branch exposure treatment for data from all 20 branches from four trees and from the 10 branches on the two injured trees (from Vann et al., SF34-2).

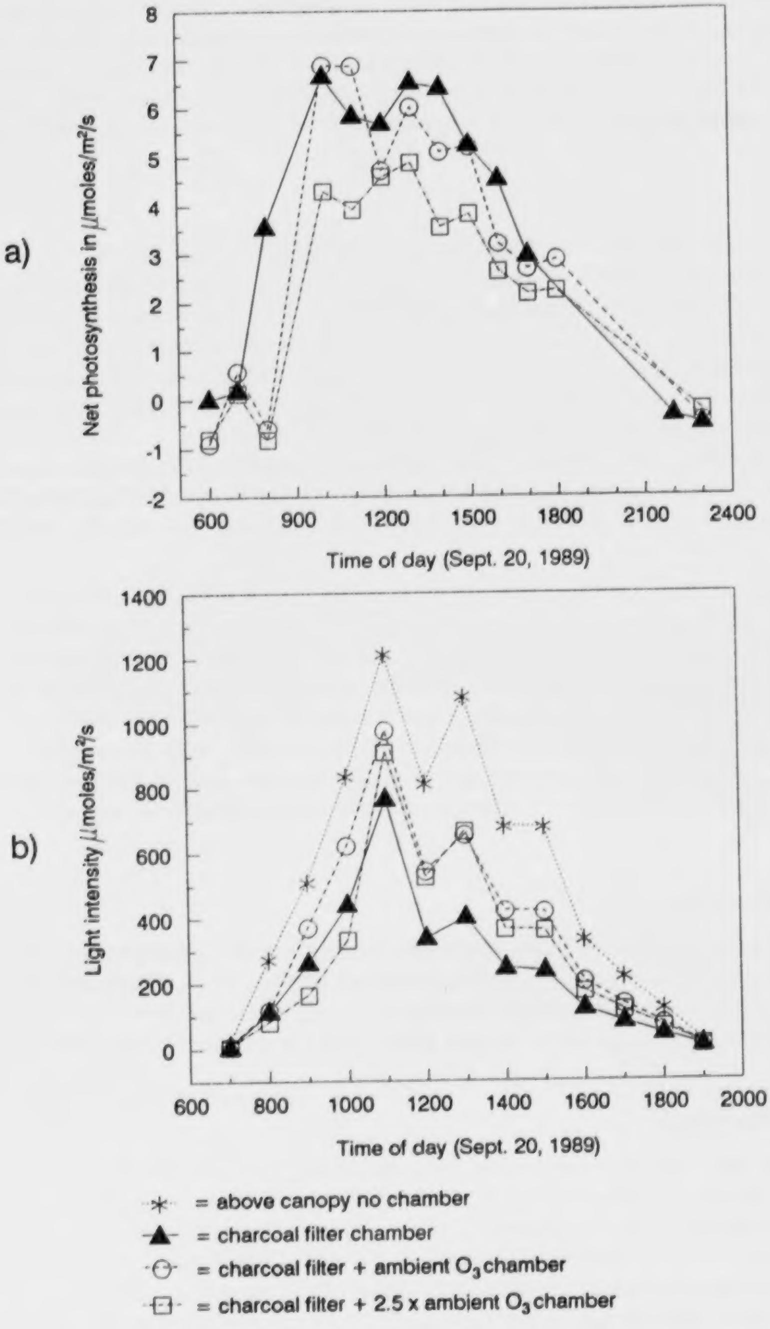


Figure 21. Diurnal patterns of: a) photosynthesis, and b) light intensity inside branch exposure chambers on loblolly pines receiving different O_3 treatments (from Wiselogel, SC18-3).

exposure, there were significant acid and acid x O_3 effects on terminal length and first-order shoots. The nature of the interaction has not yet been evaluated, but for the main effect of acidity, lengths were shortest in the highest pH treatment. In addition, antioxidant ratios changed with increasing O_3 exposure in a pattern consistent with other studies. Finally, simulation model runs predicted that the 2-times-ambient O_3 treatment during the full growing season would reduce carbon gain by 8%, with maintenance of aboveground tissue maintained at the expense of root tissue.

3.3.5 Summary

More than half of the measures of foliage growth, stem growth, and root growth in the FRP seedling studies showed no effects of increased acidity in simulated acid precipitation. Of the remaining measures, where simulated acid precipitation produced either increases or decreases in growth of seedlings, southern pines and western conifers appeared to respond with increased growth more often than decreased growth (with the exception of western conifer root growth). Red spruce, Fraser fir, and eastern hardwoods more often showed decreased growth. Foliar injury occurred in most species (at or below pH 3.0), and SO_4^{2-} appeared to be more harmful to red spruce seedlings than NO_3^-. Increased photosynthesis of seedlings due to increased acidity of simulated acid precipitation was observed in four of eight studies of red spruce and southern pines. Some increases in chlorophyll content, foliar N, and stomatal conductance were also observed.

Ozone may reduce seedling growth as well as photosynthesis in both seedlings and branches of mature trees. Loblolly pine and ponderosa pine were particularly sensitive; western hemlock, other southern pines, and several hardwood species may also be sensitive. Levels required to produce reductions were typically higher than ambient concentrations in many of the seedling reports summarized in Table 4; however, more recent results (Flagler et al., SC99-20) suggest that southern pines may be affected at ambient O_3 levels. In addition to the reductions in aboveground growth, O_3 also appeared to cause reductions in root growth of sensitive species, such as loblolly pine, trembling aspen, ponderosa pine, cottonwood, Douglas-fir, and lodgepole pine.

3.4 Winter Injury

Winter injury was assessed for red spruce in seedling studies, branch exposure studies, and in measures made on branches of mature red spruce growing in the field. In seedling studies, injury is typically assessed via controlled overnight freezing of clipped branchlets followed by measurements of electrolytes leached into water. In field studies, injury is assessed by examining needle necrosis.

3.4.1 FRP Seedling Studies

There is evidence that exposure to acid mists delays the development of cold tolerance in red spruce seedlings during the autumn and early winter (Cape et al., SF14-4; see Figure 22). Cape et al. used acid composed of equimolar solutions of ammonium sulfate and nitric acid. Although the effects of acidity, S, and N could not be separated, Cape et al. noted that their results were consistent with the hypothesis that N delays frost hardiness. Subsequent data from experiments in 1988 indicate that S rather than N caused the delay in frost hardening of red spruce seedlings (N. Cape, personal communication). This result occurred even at neutral pH: ammonium sulfate mist delayed hardening relative to water, ammonium nitrate, or nitric acid.

Jacobson and Lassoie (SF06-3) did not observe any difference in the development of cold tolerance of red spruce seedlings as a result of simulated acidic mists applied during the growing season. Jacobson and Lassoie exposed seedlings to acidic mists of pH 2.8, 3.5, and 4.2 and tested

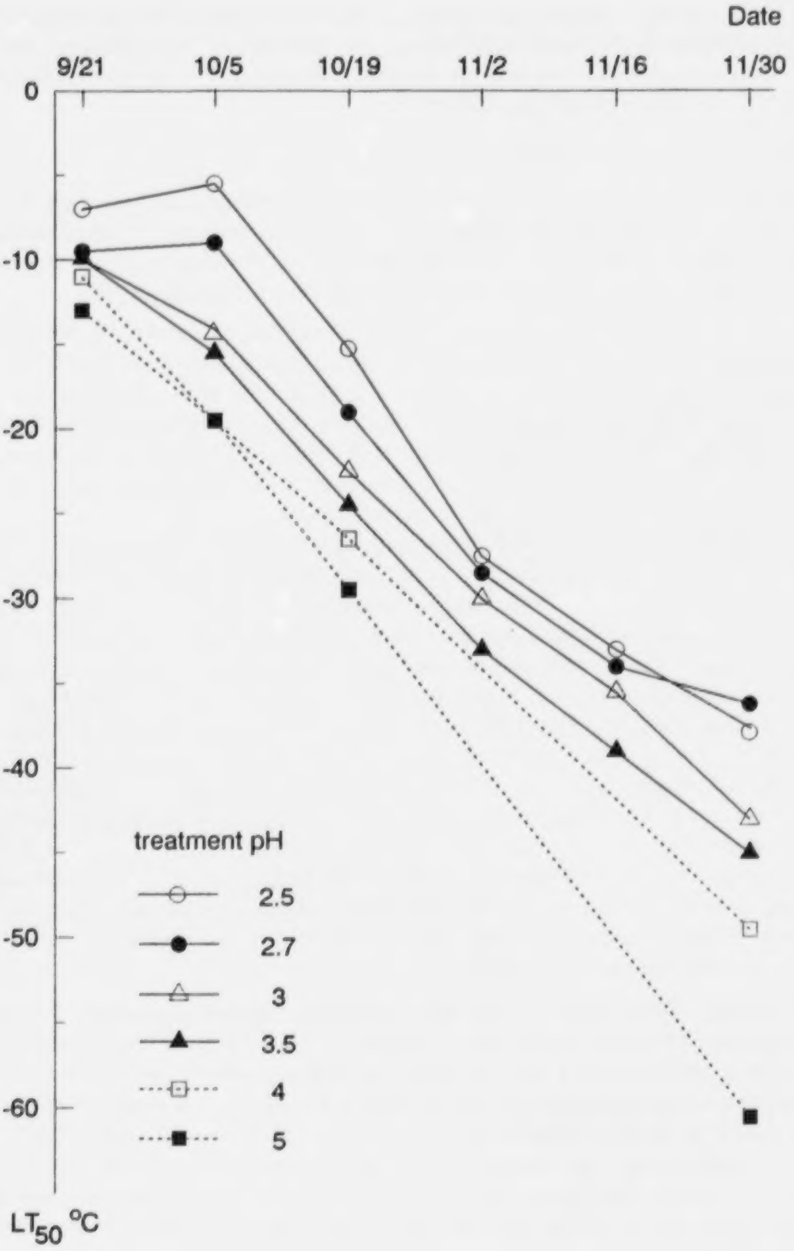


Figure 22. Delayed cold tolerance in red spruce seedlings exposed to one of six acidic mists and tested during the autumn hardening peroid. Vertical axis is the threshold temperature for a 50% kill, assessed via electrolyte leaching (from Cape et al., SF14-4).

cold tolerance of current-year needles to freezes twice in the autumn (September and November) and twice in the spring (early and late April). Jacobson and Lassoie did not freeze test their shoots to sufficiently low temperatures to induce tissue death in their November test. Therefore, Jacobson and Lassoie's data do not adequately address autumn hardening, but they suggest that acidic mists do not affect cold tolerance by April.

3.4.2 FRP Mature Tree and Sapling Field Studies

Vann et al. (SF34-2) studied mature branches of red spruce on Whiteface Mountain, NY. They reported decreased winter injury for treatments in which cloud mists and O_3 were filtered out of the branch chambers and clean mist was added when compared with both mature branches in a chamber with no pollutants removed and unchambered branches (see Figure 20).

Sheppard et al. (SF14-2) analyzed foliage samples that were collected during the fall and winter hardening period from normal-appearing red spruce trees at Whiteface Mountain, NY, Newfound Gap, NC, and Kilmun, Scotland, and from trees showing visible decline at Clingmans Dome, NC. The shoots were subjected to simulated overnight freezing, and necrosis was visually assessed 14 days later. The authors reported several observations: shoots withstood progressively colder temperatures throughout the hardening period; trees on average hardened to nearly the same temperatures at all sites; the start of hardening differed across sites; and there were significant differences among trees (lethal temperatures varied by 10°C among trees at Whiteface Mountain during December and January). Shoots from Clingmans Dome, the decline site, were at least as hardy as shoots from Newfound Gap. Most importantly, for trees at both Whiteface Mountain and Newfound Gap, the minimum temperature at which trees hardened decreased at a rate that was faster than the rate at which the temperature dropped, as shown in 22 years of temperature data (Figure 23). However, there were occasional minimum temperatures low enough to cause necrosis for at least 10% of the tested trees. Sheppard et al. concluded that their data provided "...only weak evidence to support the hypothesis that the trees that are suffering decline in the high Appalachians are predisposed to direct freezing injury." The authors acknowledged that this study did not test winter desiccation or premature dehardening, and that they may have been sampling only surviving shoots which would be somewhat frost tolerant. Although the authors performed a preliminary study to determine the effects of collection, shipping, and storage time on frost hardiness of needles, they did not discuss how well visible assessment of necrosis after 14 days would assay freezing injury in the field or how comparable results are to those from cell electrolyte leaching methods.

From 1986 to 1988, Wilkinson (SF19-3) studied 30-year-old red spruce growing in 12 rangewide provenances on a plantation in northern New Hampshire. Wilkinson made observations of winter injury to needles and measured radial increment and height growth. In each of the three years, radial increment was smallest for trees with the highest proportion of damaged needles in their upper crown or with the most frequent winter injury. A similar but less pronounced pattern was observed for height growth. Growth losses following winter injury were greater for trees in pure red spruce provenances than for trees in provenances that were introgressed with black spruce. The results support the contention that winter injury could be an initiating or perpetuating factor in red spruce decline.

Nicholas and Zedaker (SF25-1) reported on the physical effects of winter injury on trees. They stated that during ice storms up to 10 cm of ice could accumulate on trees. The extra weight of the ice, combined with winds measured as high as 95 km/hr, could cause tops to break off.

3.4.3 ROPIS Results

In the ROPIS East study, the cold tolerance of current-year needles of red spruce saplings showed no consistent differences during spring (April to early May) in response to O_3 or simulated acidic

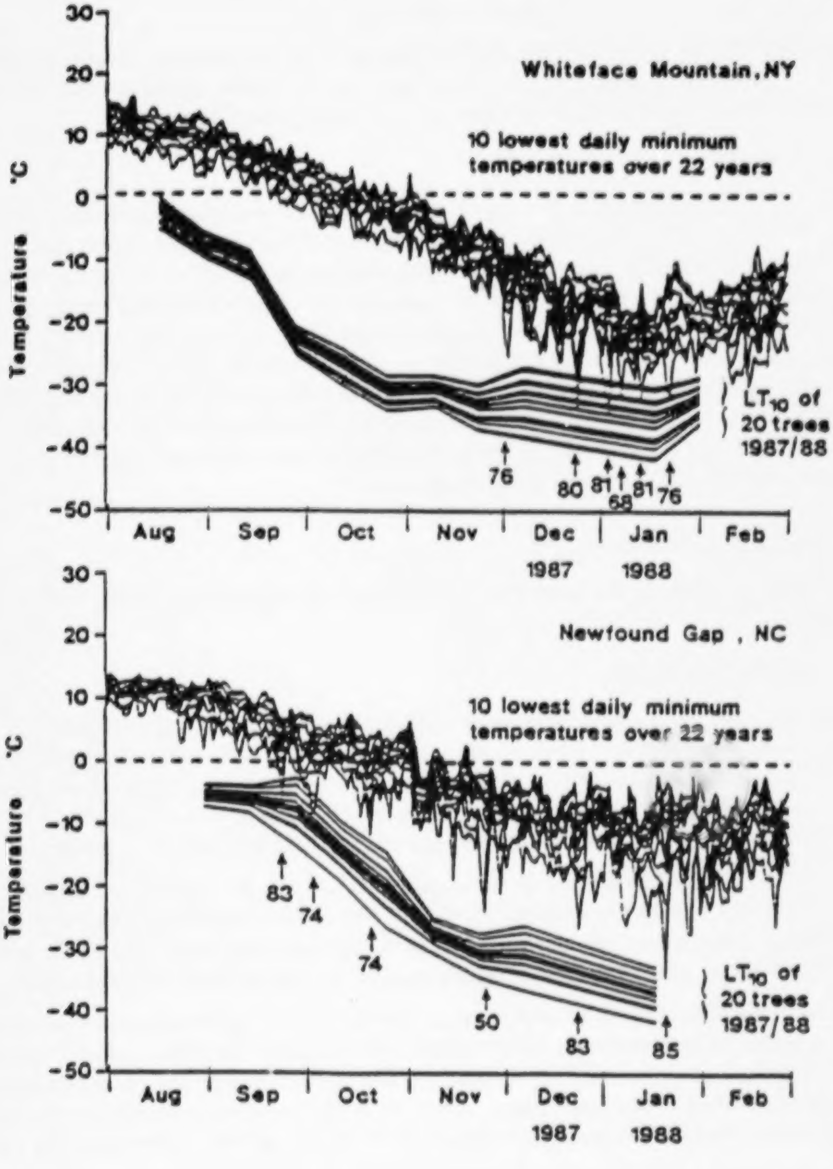


Figure 23. Change in LT_{10} (lethal temperature from a 10% kill, assessed visually) of shoots of mature red spruce from Whiteface Mountain, NY, and Newfound Gap, NC, during fall hardening period (straight lines). Lines with high-frequency variation show historical low temperatures recorded for each site. Numbers indicate years in which a recorded temperature dropped extremely low (from Sheppard et al., SF14-2).

precipitation treatments either alone or in combination. In contrast, more consistent and significant differences in cold tolerance were evident due to acidity during fall (September to early November): trees receiving pH 3.1 rain were less hardy than trees receiving either pH 4.1 or 5.1 rain, especially during middle to late October.

In the ROPIS West study, one year of O_3 and simulated acidic precipitation exposures at levels equal to those currently observed in the southern Sierra Nevada Mountains did not have any apparent effect on severity of winter injury in ponderosa pine seedlings.

3.4.4 Summary

Simulated acidic precipitation decreased cold tolerance of red spruce seedlings in controlled tests, and ambient cloud water concentrations increased freezing injury to branches of mature trees under controlled exposures. The seedling response appeared to be fairly linear as acidity increased, starting as high as pH 4.0. Other results indicate that SO_4^{2-} acids induce greater injury than NO_3^- acids. Extrapolation to field observations of declining trees may be questioned by the study of Sheppard et al. (SF14-2) in which shoots of mature red spruce trees appeared to be able to harden sufficiently to survive expected minimum temperatures. Support for extrapolation of seedling data to mature trees is provided by the branch chamber studies of Vann et al. (SF34-2) which indicate that winter injury on mature branches was associated with greater exposures to ambient clouds and gases during the growing season.

3.5 Foliar Leaching

Foliar leaching refers to the dissolution and subsequent removal of nutrients from foliage by solutions.

3.5.1 FRP Seedling Studies

Turner et al. (WC07-1) applied simulated acidic fog to western conifer species in 24 4-hr events over an 84-day period. Compared with pH 5.6, the pH 3.1 treatment increased foliar throughfall concentrations of K, Ca, and Mg in Douglas-fir. However, Turner et al. observed no concomitant decrease in foliar concentrations, and, via studies of nutrient depletion of a hydroponic solution, they estimated that root uptake could easily prevent foliar depletion due to leaching.

Patton et al. (SF07-1) exposed red spruce seedlings to 12.7 mm of simulated acidic precipitation (SO_4^{2-}:NO_3^- of 1:1) once per week for 28 weeks. Two levels of acidity were tested: pH 3.0 and 4.2. The pH 3.0 treatment increased throughfall concentrations of iron (Fe) and Mn compared with the pH 4.2 treatment for a measurement made at the end of the treatment period.

Jacobson et al. (SF06-1,2) reported decreased foliar K, Ca, and Mg concentrations in red spruce seedlings that had been exposed to acidic mists of pH 4.2, 3.4, or 2.6 for 6 to 19 weeks compared with seedlings not exposed to mists. Continuous mists produced a greater reduction in nutrient concentrations than intermittent mists. Jacobson et al. also observed acid-induced injury to foliage, but they did not observe any effects on diameter or root growth in these short-term studies.

3.5.2 FRP Mature Tree and Sapling Field Studies

Joslin et al. (SF27-1) (Table 5) compared mature red spruce trees from two sites on Whitetop Mountain, NY, that have different amounts of cloud water deposition. They reported increased solution flux of SO_4^{2-}, NO_3^-, and NH_4^+ to the forest floor and decreased foliar concentrations of Mg, Ca, and Zn at the site with higher deposition. In a similar study of saplings on Whitetop Mountain, Joslin et al. (SF27-5) reported that as the acidity of cloud water increased from pH 4.6 to 2.9, throughfall concentrations of Ca increased 18-fold, and Mg increased 25-fold. McLaughlin et al. (SF10-3)(Table 9) reported decreased foliar Ca, Mg, and P concentrations in red spruce saplings at a high-elevation site that received 30% more rainfall than a similar site 250 m lower on Clingmans Dome, NC. The lower foliar Ca reflected less soil-exchangeable Ca at the higher site. Soil-exchangeable P was greater and soil exchangeable Mg was no different at the higher site.

Liechty and Mroz (EH03-3)(Table 5) observed positive correlations between SO_4^{2-} deposition and throughfall concentrations of Ca and Mg. However, the correlations were considered to be weak.

3.5.3 IFS Results

The IFS project (described in Section 3.1.6) estimated that H^+ deposition to the forest canopies ranged from 250 to 740 eq/ha/yr for wet deposition and from 350 to 1950 eq/ha/yr for total (wet, dry, and cloud) deposition at 10 of the 17 intensive study sites, as shown in Figure 24 (Knoerr and Conklin, 1989). In contrast, there was considerably less variation in the net canopy effect (difference between total throughfall of base cations and total atmospheric deposition of base cations, which estimates cation leaching from the canopy). The net canopy effect varied by about a factor of two across the same 10 intensive study sites, as shown in Figure 25 (Ragsdale, 1989). Furthermore, no trend in H^+ deposition was evident across sites in the net canopy effect, suggesting that H^+ deposition did not directly influence cation leaching.

3.5.4 ROPIS Results

In the ROPIS South study, nutrient concentrations of loblolly pine seedlings were not affected significantly by acid, O_3, or soil Mg after one growing season. In the ROPIS East study, throughfall flux in red spruce sapling crowns was greater with pH 3.1 rain than with either pH 4.1 or 5.1, and concentrations were greater in 1988 than in 1987. Increasing O_3 exposure appeared to significantly increase the leaching of Zn from red spruce saplings. Foliar nutrition was adequate to date, but K may become deficient due to a relatively small exchangeable pool in the soil and a high plant demand.

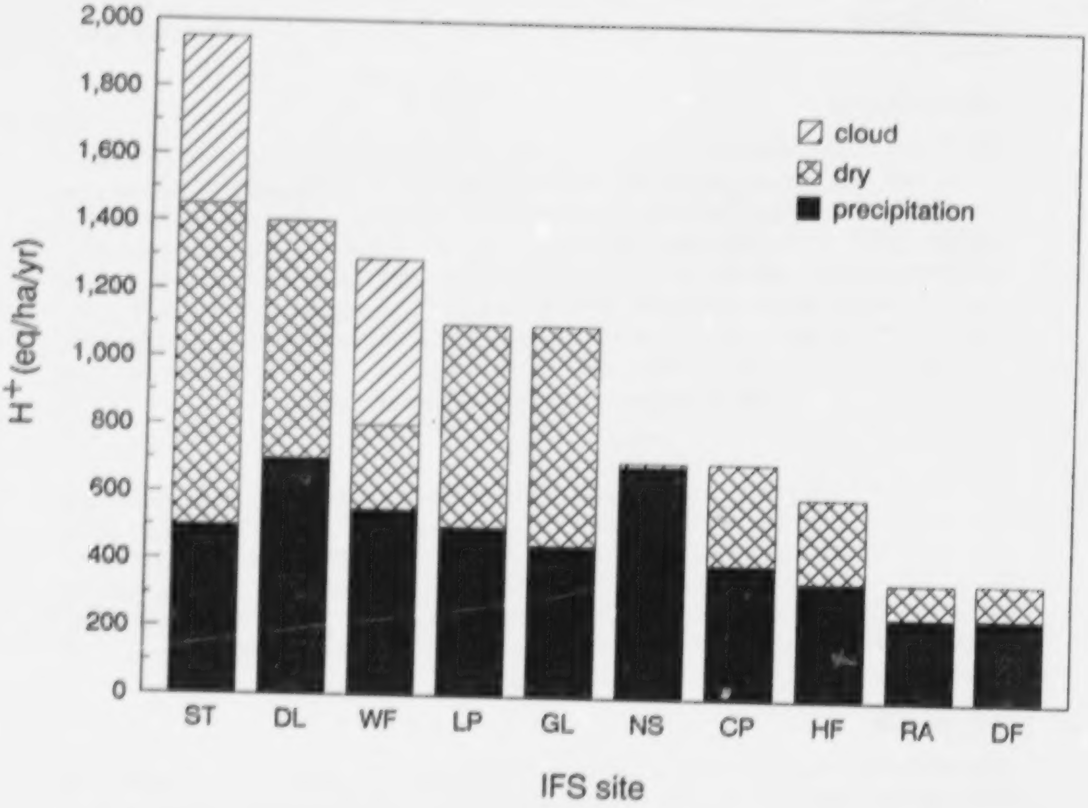
3.5.5 Summary

There is evidence that precipitation acidity can increase foliar leaching, but not dramatically (except for the study by Joslin et al., SF27-5), and the effects of canopy leaching on tree growth and health are unclear. In chamber exposures, differences occurred among species in the effect of acidic precipitation on foliar nutrient levels, with some studies showing increased nutrient levels, some showing decreases, and most showing no effect. In the field, loading of H^+ and throughfall enrichment of cations are at least weakly correlated in all of the reviewed studies. Factors such as wash-off of dry deposition, damage to cuticles by the feeding activities of canopy insects, or growth phenology, may partially mask leaching effects due to acidity.

3.6 Insects and Pathogens

Insects such as the spruce budworm, the balsam woolly adelgid, and the gypsy moth can kill large areas of forests (Millers et al., 1989). The seven FRP studies available for this review (Table 10) suggest that insects are abundant and may be a potential problem in specific areas. No relationship between insects and air pollution has been found, and limited evidence that insects may be affecting red spruce seedling survival is presented in this section.

Bruck (SF02-3) found a remarkable absence of insects (less than 5% incidence) on red spruce trees in the southern Appalachians. Hartman et al. (SF02-4) found two species of parasitic nematodes at more than 80% of their high-elevation sampling sites in the southern Appalachians, but frequency of both nematodes was either negatively or not correlated with tree decline indices.



ST, Smoky Mtns., NC
DL, Duke Forest, NC
WF, Whiteface Mtn., NY
LP, Oak Ridge, TN
GL, BF Grant Forest, GA

NS, Nordmoen, Norway
CP, Coweeta Hyd. Lab., NC
HF, Huntington Forest, NY
RA, Thompson Forest, WA
DF, Thompson Forest, WA

Figure 24. Deposition of H^+ to forest canopies at 10 IFS intensive sites (from Knoerr and Conklin, 1989).

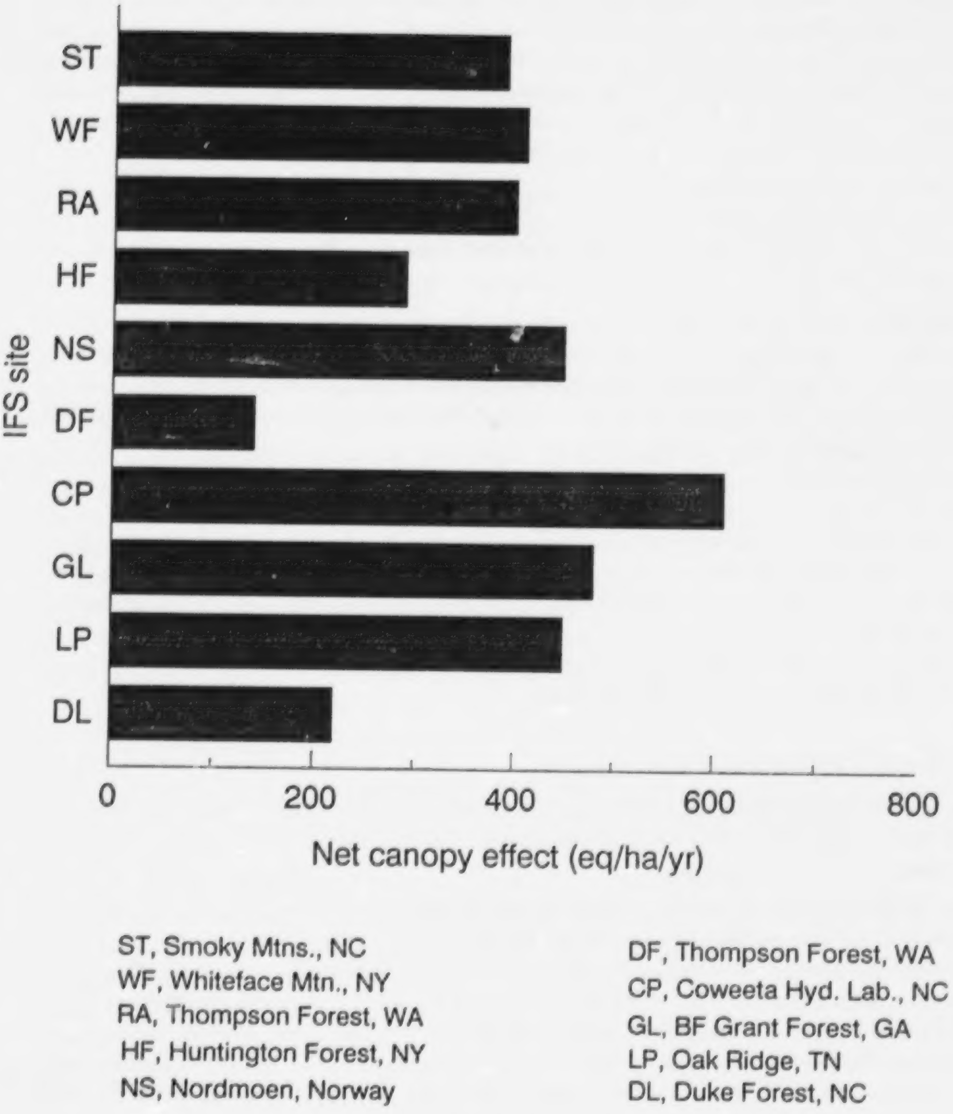


Figure 25. Throughfall enrichment of base cations in 10 IFS sites, calculated as throughfall and stemflow of base cations minus the total deposition (wet plus dry) to the canopy (from Ragsdale, 1989).

Weidensaul et al. (SF08-10), in a survey on Whiteface Mountain, NY, detected some primary pathogens such as a fir needle rust caused by *Uredinopsis* spp., but they concluded that insects and facultative parasites were not important in causing decline. Knight and Grosman (SF05-15) placed sticky-board, passive aerial barrier, pitfall, Malaise, and blacklight traps near mature red spruce and mature balsam fir trees on Mt. Moosilauke, NH, and they conducted visual searches of branches and lower boles of these trees. They found large numbers of *Korscheltellus gracilis* (Grote)(formerly known as *Hepialus gracilis* and commonly called the swift moth or ghost moth). Knight and Grosman concluded that *K. gracilis* is currently the most common and potentially damaging insect species for red spruce and balsam fir.

Tobi et al. (SF99-7) demonstrated in laboratory studies that *K. gracilis* fed on roots, causing girdling. This girdling in turn killed seedlings of red spruce, balsam fir, and white spruce. The authors found similar symptoms on large numbers of dead seedlings in the field in spruce-fir stands that were in the process of decline on Camel's Hump, VT.

Smith and Armstrong-Colaccino (SF05-12) did not observe any significant fungal infection, insect infestation, or mechanical wounding of woody or fine roots of red spruce on Mt. Moosilauke, NH. However, high densities of nematodes (10 times values found in Connecticut) were observed in the forest floor. The proportion of nematodes that were pathogenic, if any, was not determined.

On Mt. Moosilauke, NH, and Whiteface Mountain, NY, at sites from 500 to 1300 m, Grehan (SF99-16) found greatest numbers of *K. gracilis* between 700 and 1100 m, where red spruce is the dominant forest species. More larvae were found on the western windward slopes of Whiteface Mountain, which are reasoned to receive higher levels of acidic deposition than the eastern slopes due to winds and precipitation from the industrialized Midwest. Field and laboratory inoculations of spruce seedlings with feeding larvae resulted in a significant increase in foliage dieback and reduction of root mass and area. Grehan concluded that the potential impact of *K. gracilis* on red spruce should be a primary consideration in any evaluation of the effect of atmospheric deposition on high-elevation spruce-fir forests.

3.7 Reproduction and Regeneration

The hypothesis that acidic deposition may affect reproduction or regeneration was proposed early in the program but was not explicitly tested. At least two studies examined aspects of reproduction and regeneration.

Peart (SF05-1,4) surveyed red spruce and balsam fir seedling (< 1 m tall) and sapling distributions and growth patterns on the east slope of Mt. Moosilauke, NH. Red spruce seedlings occurred at much lower densities than balsam fir, and densities of red spruce seedlings were greater at 990 m versus either 840 or 1140 m. Both species exhibited J-shaped age-class distributions at the mid-elevation sites, as expected for stable populations. At low-elevation sites, both species showed markedly reduced numbers of seedlings less than 15 years old. High-elevation sites were not analyzed since red spruce was uncommon. Extension growth of seedlings and saplings of both species declined with increasing elevation, and there was a trend of declining sapling growth over the last five years. Growth of red spruce saplings was less than balsam fir, and crown condition was poorer. The percent of saplings that were standing dead increased with elevation, and overall the proportion of standing dead was higher for balsam fir than for red spruce.

Nicholas et al. (SF25-7) collected seeds in litterfall traps and also studied seedling survival in undisturbed and cleared permanent plots in spruce-fir forests in the southern Appalachians. They found that high proportions of Fraser fir (51% to 90%) and red spruce (54% to 74%) seeds were empty, but this is reported to be typical given variations in climate and activities of seed predators. Seed viabilities were higher than previous estimates made by the USFS, but were within expected ranges (31% to 87% for Fraser fir; 82% to 96% for red spruce). Seedling densities varied by mountain. Both spruce and fir seedling densities followed overstory competition densities. Spruce densities decreased and fir densities increased with increasing elevation. Seedlings germinated readily in the cleared and scarified plots. However, while spruce and fir both germinated at plots in the Mt. Rogers National Recreation Area, only hardwood species regenerated at cleared and scarified plots in the Black Mountains. Continued long-term monitoring is needed to describe regeneration success of the southern spruce-fir forests; however, seedfall, viability, and seedling densities indicate an active regeneration process.

3.8 Forest Condition Studies

Studies of forest condition in the United States, both FRP and non-FRP, have been extensively reviewed in MPO #1&2 (Reams et al., 1990). The following discussion is condensed from MPO #1&2 and from the summaries of FRP studies in Table 7.

3.8.1 Western Conifers

Chronic symptoms of O_3 damage to ponderosa pine and Jeffrey pine in the San Bernardino Mountains have been documented for over a decade (Miller et al., 1989)(Figure 26). Ponderosa pine crown condition (based on chlorosis and numbers of needles retained) and radial growth (based on tree cores) were assessed in five National Forests and two National Parks that form a contiguous north-south 500-km corridor in the Sierra Nevadas (Peterson et al., WC26-3; Peterson and Arbaugh, WC26-1). Foliar injury to ponderosa pine occurs over the 250-km southern portion of the corridor (Peterson et al., WC26-3). Although increases in radial growth since 1950 were observed as frequently as reductions over the entire corridor, reductions in growth occurred more frequently in the southern area which is closer to sources of O_3 pollution (Peterson and Arbaugh, WC26-1). Graybill and Rose (WC24-1) compared actual radial growth to predicted radial growth (using precipitation as an independent variable) for 41 sites in mixed forest stands supporting mostly ponderosa pine and Douglas-fir on the Mogollon Rim and on geographically isolated peaks in southeastern Arizona. Of the 22 sites on the Mogollon Rim, nine sites showed reductions in radial growth and one site showed an increase; for the 19 sites in the in the peaks to the southeast, 12 showed reductions and two showed increases. Cause of reduced growth was not determined; however, increased competition, air pollution, and changes in growth/precipitation relationships were suggested. Brubaker (WC25-1) observed increasing radial growth of old-growth Douglas-fir since the 1880s at sites near Puget Sound, WA, and at H.J. Andrews Experimental Forest in the Oregon Cascades. Causes of growth increases were not determined but were thought to be due to regional temperature increases.

3.8.2 Spruce-Fir

Reams et al. (1990) reviewed studies that indicate increases in mortality of red spruce at high elevations in the northeastern United States since the early 1960s. At elevations above 950 m, the percent of basal area of red spruce that is dead is much higher than that observed for other species (Friedland, SF08-17). Reams et al. noted that a similar episode of high red spruce mortality occurred in the Northeast during the period from 1871 to 1885. The exact cause of this mortality is not agreed upon, but the spruce bark beetle is known to have contributed. For the more recent episode of red spruce mortality, the cause of individual tree death has not generally been described in the surveys reviewed by Reams et al.

Crown condition of forest stands that include red spruce has been evaluated in the southern Appalachians (Bruck et al., SF02-5; Dull et al., SF26-1; Nicholas et al., SF25-6; Nicholas and Zedaker, SF25-1). Overall, no abnormally high proportions of dead red spruce have been observed. High proportions of dead Fraser fir are correlated with balsam woolly adelgid

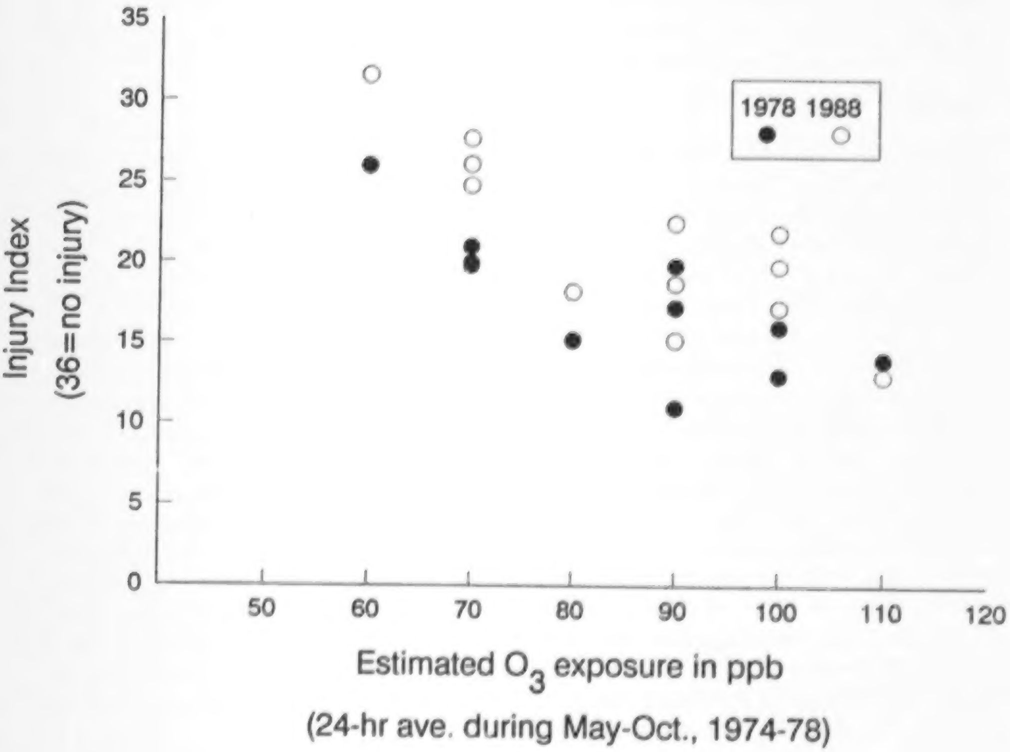


Figure 26. Crown injury (combination of needle color, needle length, needle retention, and branch mortality) as a function of O_3 exposure to ponderosa pine in the San Bernardino Mountains of California (from data presented in Miller et al., 1989).

infestations. Recent declines in crown conditions of red spruce and Fraser fir are thought to be due to droughts and ice storms.

Miller-Weeks and Cooke (VS14-3) surveyed crown condition of red spruce and balsam fir in permanent plots at a wide range of elevations (300-1200 m) in New York, Vermont, New Hampshire, Massachusetts, and West Virginia. Surveys have been conducted yearly since 1985. The authors reported a deterioration of crown condition of red spruce and balsam fir over time in all regions. Little overall discoloration in the crowns was noted, but foliage loss due to branch mortality or dieback was prevalent. However, there was no observed change in the number of recently dead trees. Reams et al. (1990) reviewed studies that have described decreased radial growth of red spruce and sometimes balsam fir in the northeast United States (see also Hornbeck et al., VS06-5) and a slight reduction of radial growth of red spruce at the highest elevations in the southern Appalachians. Initiation of growth reductions has been thought to be synchronous, beginning in the early 1960s in the Northeast and in the mid-1960s in the southern Appalachians. However, Reams et al. (1990) point out that many red spruce stands that showed growth decreases after 1960 also show growth increases during the 1950s (see also Conkey and Keifer, SF05-13). In addition, when individual trees or stands are examined, radial growth declines are not always observed and declines that are observed do not always appear to occur synchronously. Reams et al. list two hypothesized causes of red spruce radial growth reductions in the Northeast: stand or release history and frequent winter injury events in the late 1950s and early 1960s. The cause of reduced radial growth of red spruce at the highest elevations in the southern Appalachians is uncertain since factors such as stand dynamics have not been assessed. However, air pollution, climate, and the effect of the balsam woolly adelgid on Fraser fir have been suggested as contributing factors to the reported radial growth reductions of red spruce at the highest elevations in the southern Appalachians.

3.8.3 Southern Commercial Pines

In an analysis of data from the Forest Inventory and Analysis (FIA) Research Work Unit at the USFS Southeastern Forest Experiment Station, Sheffield et al. (1985) reported reductions in radial growth between 1961-1972 and 1972-1982 for pine species growing on nonindustrial private lands in the Southeast. To assess the effects of stand factors that might affect growth, Bechtold et al. (VS-04) reanalyzed the FIA data set using linear models incorporating such factors as stand age, stand density, site quality, mortality, and hardwood competition. Bechtold et al. concluded that the adjusted mean growth of pines during 1972-1982 declined by 19% in natural loblolly pine stands, 28% in natural shortleaf pine stands, and 28% in natural slash pine stands. Zahner et al. (1989) used a linear aggregate model and accounted for only a portion of the observed decreases in terms of identifiable factors such as tree age, drought, and stand density. Zahner et al. concluded that the portion of the decline that was unaccounted for was due to unidentified factors, possibly including air pollution. Reams et al. (1990) concluded that Bechtold et al. and Zahner et al. still may not have adequately accounted for changes in stand density, particularly since samples for the two periods of comparison were not taken from the same plots and appear to represent different populations. Therefore, additional research is necessary before the causes of the radial growth declines are identified.

3.8.4 Eastern Hardwoods

There is limited evidence of changes in forest condition in FRP studies of eastern hardwoods (Reams et al., 1990). Increased rate of basal area growth was observed for most hardwood species in the Northeast (Hornbeck et al., VS06-5). Witter et al. (EH03-2) observed no unusual patterns of growth or mortality in their sugar maple and hardwood plots in the Michigan gradient. Leblanc (EH05-7) observed radial growth reductions of black oak and white oak at sites along the Ohio gradient that had molar Ca:Al ratios less than 0.25 in the top 50 cm of soil. In a study of yellow-poplar, white oak, chestnut oak, and northern red oak, Smith (1990) reported that trees have become more sensitive to climate over the last 10 to 30 years. No coincident changes in climate or stand structure occurred that may have influenced this change. Brooks (VS11-1) studied forest growth along an atmospheric deposition gradient in Pennsylvania. Stand and stocking density were the best predictors of growth variation, and there was no evidence of a significant relationship between mortality and atmospheric deposition. Finally, in a North American sugar maple research project conducted jointly by the United States and Canada, Allen and Barnett (1989) reported that crown condition of sugar bushes and forest stands appeared healthy, with 89% of the sugar bushes and 92% of the forest trees showing less than 10% crown dieback.

3.8.5 Summary

Many FRP studies of forested regions produced results showing significant spatial or temporal change in some measure of forest condition. Separating the changes due to natural causes from any induced by air pollution is difficult. In the West, both increases and decreases in radial growth over time have been observed at different sites. Areas in the southern Sierra Nevada show reduced radial growth of ponderosa pine that may be related to foliar damage by O_3. An O_3 effect has already been documented in earlier studies in the San Bernardino Mountains. In the spruce-fir forests in the Northeast, a recent increase in red spruce mortality at high elevations and reductions in radial growth at high and low elevations appear to have occurred. Repeated winter injury during consecutive or closely spaced years is one likely explanation for red spruce mortality suggested by Reams et al. (1990) in MPO #1&2. Stand history was identified in MPO #1&2 as a likely explanation of reduced radial growth of red spruce. Radial growth of southern pines has declined recently on natural stands in the Piedmont. Again, the exact role of natural factors is not yet clear, and relationships with air pollution have not been conclusively demonstrated. Hardwoods have shown increased growth rates in recent years in the Northeast. Along the Ohio River Valley, gradient reductions in radial growth of black oaks and white oaks have been observed. The reductions appear to be correlated with low soil Ca:Al ratios.

4 SUMMARY AND CONCLUSIONS

4.1 Purpose of this Document

The FRP was developed to determine the nature and extent of the effects of acidic deposition on trees and forests of the United States. The purpose of this document is to address two environmental policy questions:

1. Is there significant forest damage in North America caused by acidic deposition, alone or in combination with other pollutants?
2. By what mechanisms does acidic deposition, alone or in combination with other pollutants, contribute to forest damage in North America?

To answer these questions, we first summarized research on changes in forest condition (discussed in Reams et al., 1990) and controlled exposures of seedlings to pollutants (discussed in Peterson et al., 1989). We then discussed additional research on soil chemistry (Section 3.1), roots and mycorrhizae (Section 3.2), altered carbon allocation (Section 3.3), winter injury (Section 3.4), foliar leaching (Section 3.5), insects and pathogens (Section 3.6), reproduction and regeneration (Section 3.7), and forest condition (Section 3.8). Here we summarize and then integrate these findings to draw conclusions about the potential effects of atmospheric pollutants on tree and forest condition.

4.2 Summary of Principal Findings

4.2.1 Soils

Several observations support the hypothesis that atmospheric deposition of acidic or acidifying compounds, such as H^+, SO_4^{2-}, NO_3^-, and NH_4^+ significantly alters soil chemical properties. Changes in soil chemistry similar to those that would be expected as a result of soil acidification were observed along four regional gradients of increasing SO_4^{2-} deposition in eastern hardwood forests. When compared with lower elevations on Mt. Moosilauke, NH, and Whiteface Mountain, NY, changes in soil chemistry were observed at high-elevation sites where deposition of SO_4^{2-} increases due to increased cloud water deposition. The observed trends include increases in soil total S along the eastern hardwood gradients, and increases in soil exchangeable Al and decreases in soil exchangeable base cations (notably Ca and Mg) at the mountain sites. At high elevations in the Appalachians, seasonal changes in soil solution Al^{3+} concentration are highly correlated with seasonal changes in solution NO_3^- concentration, suggesting Al^{3+} may be mobilized by NO_3^-.

Changes in soil chemical properties can result naturally and have been found to be highly variable on spatial scales as small as meters. The observed trends in soil chemical properties could be caused by factors other than atmospheric deposition, such as cation uptake by vegetation, accumulation of litter, harvesting practices, and weathering. Data are generally lacking to link deficiencies in soil cations with changes in forest condition such as mortality, reduced growth, or damage to crowns.

Measurable soil chemical changes (i.e., decreases in base saturation, increases in exchangeable Al, or increases in soil solution ionic concentrations) can be induced with additions of simulated acidic solutions. In some cases, significant changes were not detected unless very acidic solutions were applied (e.g., pH 2.5 versus 5.5). In another case, a decrease of one pH unit (i.e., 4.3 versus 3.3) caused a decrease in exchangeable Ca and Mg and in base saturation. Applications of solutions with acidities equal to those observed in throughfall solutions caused increased solution concentrations of Ca, Mg, and Al in leachate (when compared with applications of distilled water).

4.2.2 Roots and Mycorrhizae

Responses of seedling root growth to simulated acidic precipitation were highly variable. No consistent effects of acidity on growth or mortality of roots were evident in these studies. However, most soils are buffered against rapid changes in pH. Thus, to detect potential effects on roots via changes to soil chemistry (such as S and N fertilization, loss of cations, and mobilization of Al), several years of treatment will be necessary.

Root growth of loblolly pine, trembling aspen, Douglas-fir, ponderosa pine, and lodgepole pine seedlings was reduced by O_3 levels above ambient. Reduced carbon translocation to roots is a possible mechanism for this effect. Mycorrhizal frequency may be reduced and morphotype distributions may be altered by O_3; however, this work is still preliminary.

4.2.3 Carbon Allocation

In seedling studies, tested pH values ranged from 2.1 to 5.6, with typical values from pH 3.0 to 5.0. Compared with control treatments (i.e., the highest pH value used), most studies showed no effects of increased acidity on foliage biomass, stem growth, or root growth. In studies where effects were observed, southern pines and western conifers responded with increased growth more often than decreased growth. Red spruce and black cherry more often showed decreased growth than increased growth in experiments where pH 3.0 was the lowest pH value tested. Foliar injury occurred in most species at or below pH 3.0. Increased photosynthesis of seedlings in treatments with increased acidity of simulated acidic precipitation was observed in some studies of red spruce and southern pines. Increased aboveground growth coupled with no apparent effects on belowground biomass in western conifers at pH 2.1 compared with pH 5.6 indicates that changes in carbon allocation patterns occurred.

Ozone exposures in seedling studies ranged from charcoal-filtered air to 320 ppb, with typical values ranging from charcoal-filtered to 3-times-ambient concentrations (ambient site concentrations ranged from 33 to 48 ppb). Compared with control treatments (i.e., the lowest O_3 level), O_3 exposure led to decreased growth in most studies. Loblolly pine, ponderosa pine, and western hemlock showed decreases in above- and belowground growth. In addition, loblolly pine showed reduced photosynthesis. Photosynthesis was not measured for ponderosa pine and western hemlock. Most eastern hardwood species tested showed foliar injury in response to O_3, and several hardwood species showed decreases in stem mass. Levels of O_3 required to produce reductions were typically higher than ambient concentrations, although recent results showed decreased photosynthesis in seedlings and branches of mature loblolly pine at ambient O_3 concentrations (i.e., 40-50 ppb).

4.2.4 Winter Injury

In a controlled test of simulated acid precipitation, increasing acidity decreased the rate of development of cold tolerance of red spruce seedlings. Seedling response was fairly linear as acidity increased, starting as high as pH 4.0. Solutions containing sulfuric acid caused greater injury than solutions containing nitric acid. When ambient cloud water was filtered from branch exposure chambers, freezing injury decreased for branches of mature red spruce in the field. Although hardening rates differed among sites, shoots of mature red spruce trees appeared to be able to harden sufficiently to survive expected minimum temperatures. Reductions in radial growth, basal area increment, and height growth were associated with degree of over-winter injury to needles of 30-year-old red spruce trees growing in a provenance test site in northern New Hampshire.

4.2.5 Foliar Leaching

Precipitation acidity can increase foliar leaching, but the effects of canopy leaching on tree growth and health are unclear. In chamber exposures, species differences were observed with respect to the effects of acidic precipitation on foliar nutrient levels. Some studies showed increased nutrient levels, some showed decreases, and most showed no effect. In the field, H^+ loading and throughfall enrichment of cations were correlated in all of the reviewed studies, indicating a possible effect of precipitation acidity. However, other processes may contribute to the enrichment of nutrients in canopy throughfall, such as wash-off of dry deposition, damage to cuticles by feeding insects, and increased nutrient uptake.

4.2.6 Forest Condition

In this section, we examine forest regions of the United States for consistency between a change in forest condition and the presence of atmospheric pollution.

San Bernardino Mountains and Southern Sierra Nevada

There is consistency between foliar damage (chlorotic mottle, premature needle loss, shortened needle length, and increased branch mortality) and exposure to O_3, both spatially and temporally, for ponderosa pine and Jeffrey pine in the San Bernardino Mountains of southern California. Foliar condition improved over a spatial gradient of decreasing O_3 concentration from west to east (estimated O_3 dose, 24-hr average, for May-October from 1974-1978, ranged from 110 to 50 ppb from west to east) and over a temporal gradient of decreasing concentration with time from 1974 to 1988.

There is some spatial consistency between O_3 exposure and symptomatic crown injury (needle chlorosis and needle retention) to mature ponderosa pine within a 500-km north-to-south corridor in the southern Sierra Nevada. In stands showing symptomatic O_3 injury, chlorosis is greatest in the southern sites and needle retention is greatest in the northern sites. Ozone exposure increases in the same direction as the injury increases (i.e., from north to south).

High-Elevation Spruce-Fir Forests of the Northern Appalachians

In high-elevation forests in the northeastern United States, red spruce mortality increased in the 1960s. Whether or not the change is outside the range of natural variability is not known, since mortality episodes of similar magnitude occurred in the late 1800s. However, the earlier episode occurred at lower elevations, and climate and bark beetles were suggested causal factors. In the Adirondack and Green Mountains, the percent of standing dead red spruce increases with elevation. These increases in standing dead are consistent with increasing levels of wet deposition of ions at elevations above cloud base (800 to 1200 m). However, other factors that increase with elevation, such as increased wind, lower temperatures, shallower soils, and shorter growing seasons, may be associated with the higher proportions of standing dead red spruce.

There is a weak spatial consistency between chemical properties of forest floors and mineral soils in high-elevation, spruce-fir forests on Mt. Moosilauke, NH, and Whiteface Mountain, NY, and cloud water deposition. Soil chemical properties show decreased base saturation and increased exchangeable Al at high elevations when compared with low elevations.

Eastern Hardwoods

There is consistency between spatial trends in atmospheric deposition of SO_4^{2-} and spatial trends in soil chemical properties or nutrient cycling in trees. In hardwood forests in Michigan, concentrations of S in foliage and litterfall and the amount of S and N cycled in forest litter increased as SO_4^{2-} deposition increased. In the Ohio River Valley, increased concentrations of total soil S, decreases in soil pH, and increases in soil C have been found. In Pennsylvania, sap concentrations of Ca in red maple varied directly with atmospheric deposition of Ca. Although substantial changes in forest condition have yet been associated with deposition patterns, recent reductions in radial growth of white and black oak are associated with low soil Ca:Al ratios. Research is still in progress.

Southern Pines

FIA surveys of natural southern pine species on nonindustrial private land in the Piedmont indicate a reduction in average radial increment in the last survey (1977-1985) when compared with earlier surveys (1957-1966 and 1966-1977). In one study, the observed changes in radial growth were modeled using a number of factors known to affect growth (such as tree age, density, and drought). Part of the growth decline was attributed to increased competition, part to drought, and part to unknown factors. Air pollutants have been suggested as one of several possible causes of this reduction. Because O_3 exposures to these stands are unknown both spatially and temporally, the analyses cannot be considered to be a demonstration of spatial or temporal consistency between change in forest condition (reduced growth) and O_3.

4.3 Answers to Policy Questions

In this section, we address the policy questions stated earlier: that is, is there significant forest damage in North America caused by acidic deposition, alone or in combination with other pollutants, and by what mechanisms might acidic deposition and other pollutants contribute to forest damage?

Uncertainty exists in our answers to these questions for several reasons. First, our understanding of acidic deposition and O_3 exposures in many of the forest regions studied is incomplete. At many of the sites where forest condition is assessed, atmospheric deposition and O_3 levels must be inferred from data collected at sites in other locations. In some regions, such as those containing mountainous terrain, deposition can vary considerably over short distances. For example, at two sites within 100 m of each other on top of Whitetop Mountain, VA, annual deposition of SO_4^{2-}, NO_3^-, and NH_4^+ to the forest floor differed by 15%, 29%, and 45%, respectively.

Second, as seedling studies show, most effects from pollutants at ambient levels are relatively subtle when compared with the known effects of other environmental variables such as drought stress, light, temperature, nutrients, insects, pathogens, and competition.

Third, most FRP studies examined the more specific scientific questions, such as the effects of pollutants on a specific seedling function or descriptions of crown condition at a given location. Program time lines and costs limited coordination between pollutant monitoring and the studies of forest condition mentioned above, considerably different exposure regimes were used among the seedling studies, and additional information necessary to interpret likely causes of observed change was not collected in surveys of forest condition. Thus, subtle effects of pollutants on forests are difficult to detect.

4.3.1 Acidic Deposition

Significant forest damage (change greater than expected) is thought to be occurring among red spruce at high elevations in the Appalachian Mountains of the northeastern United States, based on three observations of forest condition: 1) high proportions of standing dead red spruce basal area above 1000 m in the Adirondack and Green Mountains; 2) reductions in radial growth of red spruce in many regions; and 3) tree condition visually assessed to be poor or declining over time. Although the range of possible natural variation in forest condition may be quite large, the range of variability we would expect under normal conditions is probably somewhat less than what is possible. The observed changes in red spruce at high elevations may not be outside the range of natural variability, but it does appear that they are above normal expectation and are consistent with increasing levels of wet deposition. In addition, experiments with red spruce have linked acidic mists to decreased cold tolerance in seedlings and ambient cloud water to increased winter injury to mature branches. Winter injury has been associated with reduced red spruce growth in a field provenance study. These experimental and field observations are consistent with the hypothesis that repeated winter injury, exacerbated by high levels of acidic cloud water deposition, may contribute to reduced radial growth and deteriorated crown condition in red spruce. To date, no experimental evidence has demonstrated that acidic deposition may be a direct cause of increased red spruce mortality.

Significant forest damage has not been detected in the eastern hardwoods. No relationship has been established between biomass increment and spatial patterns of sulfate deposition in Michigan. However, reduced radial growth has been observed in black and white oaks on sites with low Ca:Al ratios (0.25 molar ratio in the upper 50 cm of soil) in the Ohio River Valley.

4.3.2 Ozone

Ozone has been shown to cause foliar injury, decreased growth, and increased mortality of sensitive individuals of specific forest tree species. Extensive research efforts have previously demonstrated that O_3 has caused foliar injury to sensitive individuals of white pine over much of its range in eastern North America. Ozone has also caused foliar injury, reduced needle retention, decreased photosynthesis, and reduced growth eventually leading to increased mortality (caused by the western pine beetle) of ponderosa pine and Jeffrey pine in the San Bernardino Mountains in southern California. In controlled exposures, O_3 has caused reduced growth of ponderosa pine seedlings. Ozone occurs in concentrations sufficient to cause visible injury to vegetation in most of eastern North America. Ambient O_3 levels have been shown to cause increased foliar injury to seedlings of several hardwood species and reduced growth of black cherry and possibly of yellow-poplar. However, O_3 has not been shown to be related to changes in forest condition in the hardwood forests, nor does O_3 appear to be influencing growth of red spruce.

An argument may be made that O_3 may be causing growth reductions in the southern pines, despite the fact there are no data to directly demonstrate this. Three FRP observations support this conjecture: 1) in selected instances, loblolly pine seedlings and mature branches of loblolly pine show reductions in photosynthesis at ambient O_3 levels (i.e., 40-50 ppb); 2) a reduction in radial growth of loblolly pine has been observed in natural stands in the Piedmont; and 3) potentially phytotoxic levels of O_3 have been measured in this region (43-51 ppb). However, other information limits this conjecture. A number of the seedling studies did not show reductions in photosynthesis at O_3 levels twice ambient. The reductions in growth in loblolly pine stands may be due to natural factors, since stand density changes and increased competition from hardwoods have not been accounted for in these studies. Until these uncertainties are resolved, ozone-induced growth declines of loblolly pine in the South cannot be established.

4.4 Recommendations for Future Research

4.4.1 Soils

The hypothesis that atmospheric deposition of SO_4^{2-}, NO_3^-, and possibly NH_4^+ can alter soil chemical properties in a relatively short time period (within the lifespan of trees) is still tenable. The relationship between soil chemistry and tree condition is not clear. Leaching rates of SO_4^{2-} below the rooting zone should be assessed in those areas that are suspected to be losing cations. Mineral weathering rates should be estimated (or a method developed to estimate mineral weathering) to determine if leaching rates will result in base cation depletion. The relationship between N cycling and Al mobilization in the high-elevation Appalachian forests deserves further attention.

4.4.2 Roots

Future work addressing the effects of acidic deposition on roots should incorporate root growth systems that more realistically reflect the soil nutrient regimes to which roots are exposed in the field. Research of basic root growth processes and interactions with nutrient availability should also be supported. Our lack of understanding of root functioning and growth limits our ability to interpret results from the FRP seedling studies.

Reduced carbon translocation to roots caused by ozone appears to be a tenable hypothesis that should be evaluated in future research. ^{14}C tracer work would help answer questions of short-term carbon allocation. We still lack understanding of C and energy requirements of roots for growth, maintenance, and transport processes; both applied and basic research in this important area of tree ecophysiology should be supported.

4.4.3 Carbon Allocation

Results appear to be more consistent and interpretable when exposures are performed for at least two growing seasons. Several years of exposure may be required to obtain data sets that show the effects of O_3 at ambient levels, if any effects exist. Ozone studies should attempt to define minimum levels at which a species will show chronic reductions in physiological or growth processes. Several studies that examined tissue chemistry results suggested O_3 effects on starch, protein, N concentrations, mesophyll cell disruptions, and cuticle wax formation. Process-level studies should be encouraged. Studies of acidic precipitation should focus on interactions with nutrient availability and growth, particularly in red spruce stands at high elevations. Areas that warrant attention include leaching of Mg and Ca, SO_4^{2-} deposition, and the interactions of Al, Ca, and NO_3^-.

4.4.4 Winter Injury

The hypothesis that winter injury of red spruce at high elevations is increased by acidic compounds in cloud water and precipitation appears to have received the most experimental support of all the hypotheses tested in the FRP. Continued research of the mechanism of winter injury is recommended. The extent to which trees may be affected in the field should be determined. The linkages, if any, between winter injury, reduced radial growth, and tree mortality must be examined if the Policy Questions raised at the beginning of the FRP are to be answered.

4.4.5 Foliar Leaching

In future leaching studies, foliar chemistry and soil nutrient availability should also be evaluated. Red spruce at high elevations, where cloud water inputs are high and nutrients may already be limiting, are most likely to be affected by foliar leaching.

4.4.6 Forest Condition

Studies should test whether changes in foliar and crown condition, mortality, and growth rates are associated with each other, and the factors responsible for variability in these measures of forest condition should be evaluated. For example, better identification and characterization of natural factors associated with mortality are necessary (i.e., information necessary to characterize competition, soil moisture availability, climate, and atmospheric deposition), as are empirical models of mortality rates.

The usefulness of dendroecology research can be enhanced in several ways. Work is needed to determine the magnitude of potential bias in dendroecology procedures and the implications of extrapolating modeling results to future climate scenarios. Threshold and cumulative weather variables should be developed. Stand history must be adequately considered in relationship with climate and atmospheric deposition, and better growth and yield data and analyses might indicate that many growth reductions are associated with natural factors. Neither dendroecology nor forest mensuration alone has produced an approach that satisfactorily accounts for regional scale changes in forest productivity. On one hand, traditional dendroecology studies do not reveal stand dynamics information over time; only survivors are included (usually dominant or overstory survivors), and these individuals may not reflect stand response. On the other hand, forest growth and yield models usually reflect only stand dynamics while ignoring the influence of climate and other exogenous effects. Thus, since each approach currently quantifies the effects of important sources of variation that the other ignores, research combining forest growth and yield information with dendroecology is critical. A good starting point would be to develop sampling and analysis methodologies that address both low-frequency (stand dynamics) and high-frequency (climate) variations in tree-ring series.

4.4.7 Atmospheric Deposition

Current atmospheric deposition monitoring emphasizes point measures (mountain tops) and surrogate surfaces (i.e., not tree foliage). A shift in emphasis should be made to intensive studies of the cloud deposition process. Although monitoring of cloud deposition is useful, studies of deposition mechanisms would help to determine spatial patterns of atmospheric input into different types of forest canopies. Dry deposition of S and N should be included in estimates of atmospheric deposition.

4.4.8 Controlled Exposure Studies

Future seedling exposure studies can be improved in several ways. First, a primary source of variation in plant response is the plant material itself. Careful selection and randomization of plants prior to treatment would help to alleviate this nonuniformity. Second, correct interpretation of seedling responses among sites, or among years at a given site, requires adequate characterization of the microclimates of each site. That is, the spatial and temporal differences in factors such as light, temperature, and humidity must be known.

The statistical power of an experiment to detect treatment differences should be considered when planning research, and it should be computed at the conclusion of each project. In the absence of formal statistical significance due to low power, evidence of treatment effects may still be present in the form of trends or patterns, and these trends should not be overlooked.

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7 APPENDICES

7.1 Appendix A: Assessment of Data Quality

The goal of the FRP quality assurance (QA) program is to ensure that data used for policy formulation are technically sound and of known and documented quality. The FRP QA program was developed using existing EPA guidance (e.g., EPA 1976, 1979, 1982, 1983, 1986a,b, 1987).

The FRP QA program, which is outlined in the FRP QA Implementation Plans (EPA, 1986b, 1987), focused on the measurement process. The goal was to carry out operations and procedures so that the data produced were of specified quality within a stated level of uncertainty. Data quality was specified quantitatively as precision and accuracy for each measured variable. The specifications were developed through a concensus of scientists and expressed as data quality objectives. Precision was estimated by repeated measurements of the same materials using the same methods. Accuracy was estimated by the difference between a measured value and a primary standard, reference material, or equivalent method.

7.1.1 Use of Data Quality Assessments

The purpose of data quality assessment was not to reject project data or results, but to improve data by providing real-time information for principal investigators to use in monitoring and controlling variation due to operational or measurement procedures. The data quality objectives were used as program goals, rather than as boundaries for accepting and rejecting data. In fact, one purpose of the data quality assessments was to evaluate the degree to which data quality objectives could be realistically attained; for example, application of a pollutant at target value ± 10% (Peterson et al., 1989).

The QA staff summarized data quality assessments from each project and advised the authors of this document as requested. The authors evaluated the significance of the QA findings within the context of the whole study, making no attempt to discount project data and results solely on the basis of data quality assessments. Instead, the QA information was used with other information in evaluating and interpreting project results.

7.1.2 Quality Assurance Activities

Four general types of activities were carried out to assess data quality: planning, on-site auditing and performance evaluations, comparability studies, and QA documentation. Each of these are described briefly in the following paragraphs. Further details can be attained from MPO #1&2, MPO #3, and final QA reports that are now being written.

The first activity, QA planning, required projects to prepare a QA project plan. The QA staff reviewed each plan and made recommendations for improvement if necessary. Approval indicated that sufficient QA activities were planned for the project to determine and document data quality. QA project plans were developed for most FRP projects; the exceptions were those funded at the beginning of the FRP, before the QA program was fully implemented.

An annual on-site technical system audit (TSA) was required for each project. The TSAs involved a comprehensive review of the QA activities of the whole project as described in the project plan. In addition, annual air monitor performance evaluations were implemented in projects conducting controlled exposures or collecting ambient air quality data. Air monitors were evaluated by calibrating project equipment with audit equipment used as a standard to assess accuracy in comparison with a certified reference gas.

The QA staff conducted 34, 48, 38, and 45 system audits for 1986, 1987, 1988, and 1989, respectively. Air monitors at 13, 21, and 23 sites were audited for 1987, 1988, and 1989, respectively. Following each audit, a report highlighting audit findings and recommended corrective action was written. These reports were confidential and were distributed only to project personnel and the QA staff. Most recommended corrective actions were technical and were reconciled between the project personnel and the QA staff, with a follow-up by the QA staff. Occasionally, audit findings revealed management issues, such as changes in project research direction or questions regarding cooperator interactions and funding. These issues were referred to the respective cooperative manager for resolution.

The third activity, comparability studies, included promoting the use of similar measurement methods and equipment, and documenting differences among methods, laboratories, and field crews. For example, the FRP QA project funded the development of three methods manuals (Evans and Dougherty, 1986; Robarge and Fernandez, 1987; Zedaker and Nicholas 1988). These manuals contained recommended methods and were distributed for use in FRP-funded projects. Furthermore, the QA project funded 12 research initiatives on methods comparability, and managed four FRP-wide interlaboratory sample exchange programs. In 1988, there were respectively 9, 31, and 24 FRP projects participating in the soil, water, and foliage sample exchanges. Finally, the QA staff helped coordinate and evaluate group training sessions for several field survey projects.

The final activity, documentation, focused on promoting thorough record-keeping within projects in order to document QA activities and assessment of data quality. Other activities included maintenance of QA project plans and audit reports, collection of project QC results, and formation of a database of project summaries and QC data.

7.1.3 Quality Assurance Findings

Data quality assessments revealed several common problems:

1. QA project plans were not fully implemented, especially documentation of procedures and collection and use of QC data.
2. Air monitors were not calibrated within acceptable limits.
3. Application of controlled pollutant treatments within and among exposure technologies could be an important source of experimental error (Peterson et al., 1989).
4. Some chemical elements in foliage and soil reference samples varied notably among laboratories.
5. Bias existed in analytical results due to the method by which experimental material was either sampled or measured.

The significance of these findings varies depending on the particulars of the project and how the data were used. For example, the significance of an air monitor miscalibration depended primarily upon when it was discovered. Fewer data were compromised the earlier the detection within an exposure treatment or season. Thus, equipment audits were scheduled and conducted as early as possible for each project. Differences among laboratories or measurement methods can be an important consideration, given the goal of summarizing data across several projects.

For several reasons, no studies were excluded from this document because of QA findings. First, the purpose of the QA program was to improve data quality by detecting problems early and preventing their repetition. This process also allowed questionable data to be identified, but this was not the primary goal of the improvement process. Second, the QA program focused on the measurement process. Failure to meet a data quality objective or recognization of method bias raised concerns, but it was not sufficient cause for completely dismissing project data and results. Numerous other factors must be considered before the quality of a project can be fully evaluated, such as sampling design, statistical analysis, selection of treatment levels, and the nature of the experimental material. The QA information was thus properly used in conjunction with other project information during the evaluation and interpretation phases. Third, some QA guidelines are qualitative, and they may thus be interpreted in different ways. For example, lack of documentation of project procedures or remeasurement data does not necessarily indicate that work was poorly done, although it does mean that evidence of good work is lacking. Furthermore, the level of documentation that will satisfy a data user may vary. Lack of documentation may add uncertainties, but it alone is not cause for rejecting project data or results.

These findings illustrate situations in which projects did not meet QA guidelines. More detailed QA reports are in preparation. Results that are indictative of the accomplishments of the QA program include: 1) increased documentation of projects; 2) increased use of standardized methods and better appreciation of the need to have comparable data; 3) improvement in data quality due to audits and introduction of QA concepts; and 4) increased ability to quantify estimates of data quality.

7.1.4 Quality Assurance of Branch Exposure Chambers

An overall goal of the FRP is to assess the effects of atmospheric deposition on forest stands. Much of this work has used controlled exposures of seedlings, as discussed in MPO #3. The QA findings for open-top chambers (OTCs), continuously-stirred tank reactors (CSTRs), and growth chambers used in the seedling research are discussed in detail in MPO #3. Branch exposure chambers (BECs) have been proposed as one method for assessing the effects of air pollution upon mature trees. In this section, we review QA findings for branch exposure chambers.

The BECs are a relatively new technology, and they present both conceptual and operational difficulties that must be overcome before results are considered reliable. Data reliability of BECs depends in part on how well ambient environment is maintained and pollutant treatments are controlled. Peterson et al. (1989) have shown that variation in the application of pollutant treatments in OTCs, CSTRs, and growth chambers may be an important source of experimental error in plant effects studies. They reported that some FPR QA guidelines for exposure research were difficult to meet consistently. Consequently, a similar analysis of BECs was undertaken for this document.

On the basis of three projects, BECs appear to be reliable. Although results are preliminary and do not cover all aspects of BEC use, they do represent two to three years of work per project on the development, testing, and use of BECs under lab and field conditions. For example, BECs appear to meet or exceed FRP guidelines for maintenance of the ambient environment. Data from Wiselogel [SC18-3] in Figure A1 show that chamber temperature was within 3°C of ambient temperature outside the chamber, which is the FRP guideline (Evans and Dougherty, 1986). In addition, other data from Wiselogel (SC18-3) showed that hourly chamber temperatures varied less than 1°C among chambers on the same tree. Similarly, Vann et al. (SF34-2) found that mean air temperature was 1.1 to 2.4°C greater in chambers compared with open branches on the same tree during a 20-day period in late summer, 1988. Chamber temperatures showed consistency among trees; within any given treatment, mean chamber temperatures varied less than 2°C across trees.

Figure A2 shows that chamber light intensity is within 10% of ambient, which meets the FRP recommended guideline and easily exceeds the FRP control limit of 25% less than ambient (Evans and Dougherty, 1986). These differences from ambient were found in full sunlight and are due to light absorption of the Teflon skin. Wiselogel [SC18-3] has shown that the skin reduced light transmission up to 200 $\mu mol/m^2/s$; therefore, chamber light intensity would be within at least 25% of ambient during midday throughout the growing season.

The BECs are capable of meeting or exceeding FRP guidelines for control of pollutant concentrations. Figure A3 shows that O_3 concentrations can be delivered within 10% of target, which meets the FRP control limit (Evans and Dougherty, 1986). Houpis (WC20-1) found no significant O_3

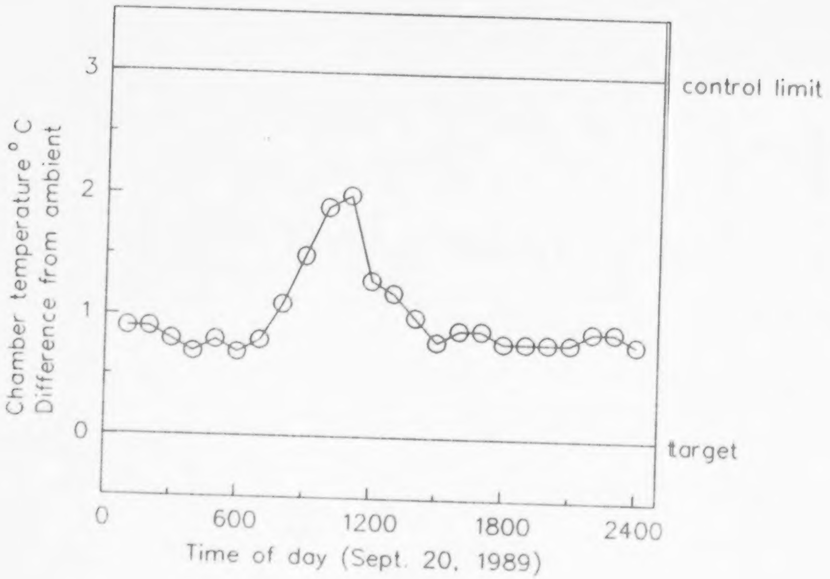

Figure A1. Example of diurnal chamber air temperature in relation to ambient (target) and FRP control limits. Charcoal-filter + ambient O_3 chamber shown. Other treatments were within 1°C (adapted from Wiselogel, SC18-3).

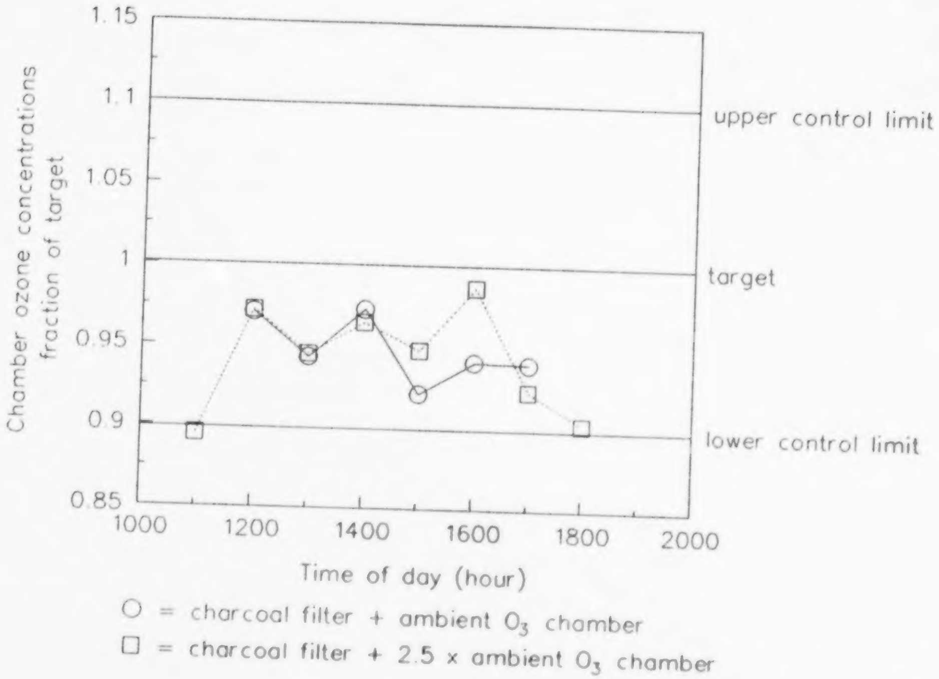

Figure A2. Example of diurnal trend in O_3 concentrations (actual/target) for two treatment chambers on the same loblolly pine tree in relation to FRP control limits (adapted from Wiselogel, SC18-3).

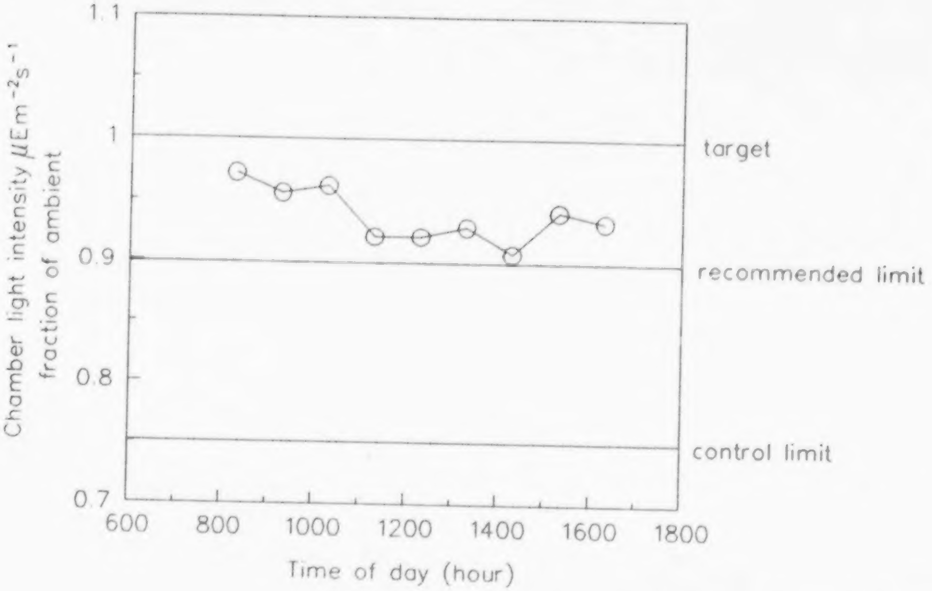

Figure A3. Example of diurnal trend in light intensity in relation to ambient (target) and FRP control limits (adapted from Houpis and Cowles, WC20-1).

gradients within BECs (mean maximum difference among test points was 6 ppb). In addition, O_3 concentrations surrounding and inside a branch canopy differed by only 4 ppb. Finally, the scrubbing efficiency of the BEC charcoal filter system increased with test O_3 concentrations and varied from 79% to 88%.

7.2 Appendix B: Methods and Materials

7.2.1 Forest Condition Surveys

Research conducted to investigate the two scientific questions addressed in MPO #1&2 used an epidemiological approach, characterized by broad surveys of forest condition and a search for patterns that may be related to natural factors or atmospheric deposition. The techniques used in these studies are discussed in this section. The techniques and limitations of all survey methods are discussed in more detail in MPO #1&2.

Dendrochronological Analysis

Tree core samples are taken from the population of interest. The obtained tree rings are measured and crossdated (Fritts, 1976). Ring widths are then modeled to determine how environmental factors, both natural and anthropogenic, affected tree ring growth. Endogenous disturbances (those affecting a single tree or a subset of trees in a stand) and exogenous disturbances (those affecting radial growth across stands) must each be considered. To assess the effects of pollutants, the pollution signal must be separated from all other factors. Linear aggregate and multiplicative models have been used.

Transect Surveys

Transects of varying lengths were used to sample tree vigor class at a number of mountain sites. Transects were run at different elevations so that elevational differences in forest conditions could be quantified. In sampling, the tree nearest to the transect line that exceeds a lower size class limit is sampled. In studies cited in this document, crown classification and live/dead status were the measures recorded for each sample tree/transect. Transects or sample trees are not identically remeasured over time, as initial transects are not usually permanently marked. However, the same forest stands are represented.

Permanent Study Remeasurement Data

Permanent plots are used because the sampling error associated with remeasurement and growth and change estimates is likely to be lower than the error associated with independent samples (Avery and Burkhart, 1983). They are chosen using two criteria: 1) plots must be representative of the forest population for which inferences will be made; and 2) plots must be subject to the same management practices as the unsampled portion of the forest. To determine forest condition over time, plots of a fixed area were also used, with the number and size of plots required a function of the size and variability of the population, required sampling precision, and cost (Husch et al., 1972). Data obtained from plots typically includes both plot and individual tree measures. Examples of plot data are location, cover type, stand size and condition, stand age, stocking, slope, soil classification, and understory vegetation. Individual tree measures include species, diameter at breast height (dbh), height, crown class, vigor, diameter growth, and mortality. Because a long intermeasurement period can mask important changes in the rate of growth, long remeasurement periods should be avoided.

Forest Inventory and Analysis (FIA) Data

The Forest Inventory and Analysis (FIA) Research Work Unit of the Southeastern Forest Experiment Station inventories the forests of Florida, Georgia, North Carolina, South Carolina, and Virginia (Sheffield et al., 1985). FIA data from Pennsylvania, Minnesota, Wisconsin, Michigan, and Vermont are also collected, and are presented in this document. FIA inventories across the United States are conducted approximately every 10 years to measure changes in the population. In the Southeast, the first inventory was initiated in 1933, and the fifth was completed in 1985. There are approximately 25,000 permanent FIA plots in this region, each representing an average of 3,400 acres.

In the Southeast, inventory methods and sampling techniques have changed over the years, which has to be taken into account when interpreting survey results. For FIA remeasurement data used in the FRP, the point sampling method, generally referred to as selection with probability proportional to size, is used. The trees are selected by the basal area factor (BAF), the cross-sectional area (ft^2/acre) that a tree represents. As the BAF increases, the probability of a tree being selected decreases. The BAF system provides for rapid and unbiased estimates of stand conditions at a given point in time. In subsequent surveys, the live trees identified by the BAF in the previous survey are remeasured to calculate diameter growth.

To analyze individual-tree growth from the Southeast FIA data, average annual radial increment (AARI) is calculated for each tree and then a mean AARI is calculated for each diameter class and species. Even though the same trees are remeasured, some trees die or are cut, new trees are included, and most trees grow into larger diameter classes. Comparison of mean AARIs for successive time periods thus indicates how trees of the same diameter class grew in each period, not how growth of the same trees might have changed.

The nonindustrial lands of the Southeast surveyed by FIA are not usually as intensively managed as are private lands, and trees of all crown classes are included. High percentages of intermediate and overtopped trees in the smaller diameter classes suppress growth values. Thus, growth curves are not typical of those derived for intensively managed stands. The changes in FIA inventory design over the years make comparisons of individual-tree growth rates difficult. Individual tree growth data from the earlier surveys are limited; thus, reports of growth reductions are based on comparisons of average growth rates from the fourth and fifth survey periods only. Additional difficulties arise in determining possible causes of tree decline because some important tree, stand, and site information is not available for all plots. Missing information can include crown position, crown ratio, competing basal area of trees and shrubs, site quality and prior land use. However, some of these measures can be added to the sampling procedure.

Spatial Study Data

Spatial studies are conducted along known deposition gradients spanning large geographical areas. Fixed plots are sampled at sites along the gradient to identify patterns in forest response to natural factors and pollutants; in particular, the responses at either end of the gradient are compared to determine the magnitude of change. To minimize variation in response due to differences in stand characteristics, plots are selected to have similar stand characteristics. Responses measured along the gradient include tree growth, tree mortality, crown vigor, and precipitation, throughfall, soil, and litterfall chemistry. Spatial studies have been conducted along gradients in the Great Lakes region (Minnesota to Michigan), in the Ohio Valley (Arkansas to Ohio), and in Pennsylvania.

Aerial Photography and GIS

Maps, in conjunction with software designed to analyze large data bases of geographic information, have been used in a few instances to evaluate forest condition for a large geographic area, such as estimated standing dead. In one study, existing type maps for the area were used to identify stands of known species. The applicable maps were then transferred to aeronautical section charts, flight lines were plotted, and aerial color infrared photographs were taken in stereo at a scale that allowed individual trees to be studied under magnification. Next, photo interpreters classified by mortality the area within each of six previously defined geographic regions and determined the stand boundaries. Mortality classes were then randomly sampled in proportion to the area of tree species affected. A random ground sample of the selected aerial plots was also performed, providing data on species, dbh, crown condition, total height, and crown position for each sampled tree, as well as site information. The GIS software was used to construct the database.

7.2.2 Atmospheric Deposition Data

Wet Deposition Data

While some researchers have used survey data to evaluate forest growth and condition, other research has been conducted to assess trends across the Unite States in atmospheric deposition of pollutants and exposure to ozone. These data and the methods used to obtain the data are are presented in MPO#1&2. In that report, annual summaries of precipitation chemistry from the National Atmospheric Deposition Program (NADP/NTN) are used to describe spatial (horizontal) variation in wet deposition (NADP, 1988; Olsen and Slavich, 1986). Cloud water chemistry data from the Mountain Cloud Chemistry Project (MCCP) also are presented to describe elevational (vertical) variation (Mohnen, 1988a,b; Vong, 1990).

Elevational variation in deposition is primarily related to the amount of time a forest is immersed in clouds. In the East, at elevations below about 1000 m, wet deposition is primarily due to precipitation, while above 1000 m cloud water chemical deposition may equal or exceed precipitation deposition. Cloud frequencies and chemical flux contributions from cloud water have not yet been quantified for the West.

Either wet deposition or concentrations of H^+, SO_4^{2-}, NO_3^-, and NH_4^+ may be relevant to describe acidic precipitation, depending on the ecological effect of interest. For example, foliar leaching in spruce needles might be related to chemical concentrations in acidic precipitation, whereas soil buffering processes might reflect wet deposition. Because observed precipitation concentrations of H^+ (NADP, 1988) are consistently lower than those found to harm seedlings (Peterson et al., 1989), precipitation deposition, not concentration, is considered relevant to forest effects. However, because of the much higher chemical concentrations (lower pH) in cloud water, both cloud water chemical concentrations and deposition are considered relevant to forest effects.

Regional estimates such as isopleth maps typically are used to show the magnitude and extent of acidic deposition and to locate areas of high or low deposition. Spatial interpolation is necessary to generate contour maps of wet deposition and to estimate data for non-monitored locations. Recognizing that there are numerous equally valid methods for presenting these data, a regional map with bars was used because it best demonstrates annual deposition, its variability, and gradients over regional scales (< 100 km). Contour maps require interpolation assumptions and can mask some small-scale variability, but they are also very useful for displaying large-scale spatial trends (over areas greater than 100 km; Vong et al., 1989; Olsen, 1989). To produce summaries, multiannual averages from only NADP/NTN sites were specified to ensure data comparability and reduce temporal variability. Contour maps for individual years are available elsewhere (summarized by Vong et al., 1989).

Ozone Data

Ozone is the only regionally dispersed pollutant known to injure foliage and cause tree mortality (Woodman, 1987). Ozone injury to coniferous forest species is well documented (e.g., Miller et al., 1963; Miller, 1973, 1984; Peterson et al., 1987; Peterson and Arbaugh, 1987; Temple, 1988). Regional and national trends in O_3 exposure are reported in MPO#1&2. However, because O_3 levels are not known for the forested sites in FRP studies, formal correlations of O_3 levels and forest growth and conditions were not possible in either MPO#1&2 or this report.

Several indices of O_3 exposure have been used, such as simple 24-hour means and cumulative or weighted sums. When relating growth trends to pollutant exposure across large spatial areas, these indices may not reflect subtle differences in O_3 exposure (and consequently response) at different places. Because the "physiologically effective" dose for O_3 is the integrated flux into leaves via the stomata, the correspondence between diurnal patterns of stomatal conductance and O_3 concentration determines the effective dose (Guderian, 1985; Krupa and Teng, 1982; Tingey and Taylor, 1982). Thus, differences in diurnal O_3 patterns may produce different physiological responses, and therefore an index that incorporates both the temporal aspect and the magnitude of O_3 concentration is desirable.

Since the formation of O_3 is related to meteorology, which can vary considerably from year to year, the median can be influenced by the sampling period. To reduce the likelihood of such influence, periods longer than three years were usually used for averaging. Worst-case scenarios can also be influenced by sampling period, but at worst they will underestimate extreme conditions. Seasonal and diurnal patterns in O_3^{med} and O_3^{worst} do not reflect actual patterns, but are rather 50th percentile and 99th percentile surfaces.

7.2.3 Controlled Exposure Studies

Research conducted to investigate Scientific Questions 2.2, 2.3, and 2.4 uses an ecological approach, characterized by controlled exposures of seedlings in chambers to simulated acidic deposition and gaseous pollutants. Results from seedling studies, such as visible or latent seedling response, are the major source of information currently available to address the scientific questions. The term seedling refers to trees small enough (e.g., height generally less than 1 m) to be housed in standard open-top chambers. The techniques and limitations of these methods are discussed in detail in MPO #3. Thus, only a brief summary of the technique is given here.

General Methods

To quantify responses to simulated acid deposition, SO_2, and O_3, 12 conifer species, 12 hardwood species, and 100 commercially important families of loblolly pine were tested. Most studies used seedlings, but studies performed with branch exposure chambers used mature trees. This section describes the general methods used. Methods varied among studies and may have affected the particular results observed. A more complete overview of the experimental approaches used in individual research projects by the four research cooperatives is given in MPO #3.

Experimental Material

Seedlings were grown from germinated seeds obtained from known seed sources. These sources were: 1) specific regions of forest occurrence for spruce fir; 2) tree nurseries for the eastern hardwoods; 3) commercial and research seed orchards of loblolly pine; and 4) regions of forest occurrence and forest-tree nurseries for western conifers. Most seedlings were planted in individual containers. Rooting media were typically composed of commercial mixtures (e.g., peat, vermiculite, perlite), although soil representing a forested site was sometimes used. Ages of seedlings at time of treatments ranged from 12 weeks to 4 years; the majority were 2 years or younger at the beginning of the studies.

Exposure Facility

To apply treatments to seedlings, chambers were used that provided for delivery of simulated acid deposition and that allowed some modification of the air space around the seedlings. Two types of chambers were generally used, and choice of chamber type involved a trade-off between experimental control and replication of realistic conditions. Completely enclosed chambers, referred to as continuously-stirred tank reactors (CSTRs) in greenhouses or laboratories allowed for higher precision in the application of gaseous treatments. Most exposure facilities were open-top chambers (OTCs), located outdoors where some exclusion of ambient air, but exposure to sunlight, humidity, and normal air temperatures, was desired. The outdoor chambers may or may not have had rainfall exclusion devices, depending upon experimental objectives.

Branch Exposure Chambers

Branch exposure chambers were used to assess the effects of air pollution on large, mature trees. These chambers enclose tree branches for the purpose of controlling pollutant exposure by filtering ambient pollutants and/or by delivering known levels of pollutants. Modification of the ambient environment within chambers is common; in particular, temperature, light, and air humidity are controlled. Branch exposure chambers incorporate features such as fans to promote air exchange, materials that allow light penetration but do not hold heat, and humidifiers. In addition to being influenced by these technical concerns, the reliability of results from branch chamber studies is also influenced by conceptual issues such as branch autonomy, sampling design, and integration with root processes.

Treatments

The most prevalent treatments included simulated acid precipitation and O_3 applied alone or in combination. One to six levels of acidity were used, ranging from pH 2.1 to 5.6. Simulated acid precipitation typically consisted of a chemical composition that reflected rainfall chemistry of the study area (S:N typically 2:1). In MPO #3, terms such as acidity, acid, or acid deposition refer to H^+ concentration plus the chemical composition of the simulated precipitation.

One to six levels of O_3 concentration were used, ranging from 0 to 320 ppb. Charcoal filtering can remove up to 100% of O_3 in ambient air. Therefore, CSTRs can attain 0 ppb treatments while OTCs never quite approach 0 ppb due to mixing of filtered air and ambient air through the open tops. Concentrations of O_3 in OTCs that receive charcoal-filtered air are typically 30% to 50% of ambient concentrations. In addition to acidity and O_3, one project varied the ratio of S to N in the precipitation, while others applied treatments of SO_2. Finally, several studies tested for interactions of acid precipitation and/or O_3 with winter injury or interactions with water stress.

Treatments were applied to the seedlings during periods of active aboveground growth over intervals varying from 10 weeks to 7 months. Multiple-year exposures are also being carried out.

Simulated deposition was applied as rain, mist, or fog, usually to both foliage and rooting medium in a pattern reflecting historical trends for a specific region. In some cases, deposition was applied only to saturate the foliage; in such cases, the rooting medium received controlled watering. Ozone was applied over regulated time intervals, usually during daylight hours. Applications varied among studies, but were of two general types. One type was a square-wave regime where a constant concentration of O_3 was applied over a definite time interval during the day. In more sophisticated designs, O_3 applications followed the monitored ambient concentrations for the region, where O_3 concentrations typically increased to a mid-afternoon peak then decreased until dusk.

Response Variables

Response variables measured are either effects or mechanisms. Effects represent a change in seedling condition and include visible injury or growth changes. Mechanisms are the processes by which effects are manifested. The mechanisms examined include carbon allocation, winter injury, and foliar leaching, reflecting Scientific Questions 2.2, 2.3, and 2.4. Carbon allocation is used as a general term that includes growth, morphology, and general physiology, including photosynthesis and respiration.

The actual response variables measured in some studies were quite numerous. Some variables were measured several times during the treatments, while others were measured only at the termination of treatments. Visible effects included foliage discoloration (chlorosis, necrosis), foliage loss (senescence), or whole-tree subjective classification. Growth effects involved some measure of seedling biomass (linear measures of branches or roots, diameter of stem, or mass of various components). Carbon allocation involved measures of photosynthetic rates, respiration rates, tissue damage assessed microscopically, or tissue chemistry (sugars, starch and nonstructural carbohydrates, photosynthetic pigments, or enzymes). Winter injury was examined as an interacting stress; in these cases, seedling responses were measured after treated seedlings were allowed to over-winter at ambient temperatures or after tissues were exposed to simulated frosts. Foliar leaching involved some measure of solution chemistry of throughfall or of solutions in which treated tissues were leached.

Statistical Methods

All seedling studies were designed to test hypotheses statistically. Building on exposure studies of crops in the National Crop Loss Assessment Network (NCLAN), the experimental designs were generally a variation of split-plot or randomized blocks. Most studies were designed for repeated measures (usually five or more intervals) of total plant height and root collar diameter. Data were analyzed via analysis of variance, analysis of covariance, or regression techniques. Important statistical issues identified for the seedling exposure experiments are design and analysis, relevance, combining results across experiments, and statistical power. These issues are covered in MPO #3 and elsewhere (Peterson, 1989).

7.3 Appendix C: Abbreviations

AARI	average annual radial increment
AIRS	Aerometric Information Retrieval System
ALBIOS	Aluminum in the Biosphere
A	ambient
BAF	basal area factor
BEC	Branch exposure chamber
CF	charcoal-filtered
CSTR	Continuously-stirred tank reactor
dbh	diameter at breast height
DDRP	Direct/Delayed Response Program
EH	Eastern Hardwoods
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
FIA	Forest Inventory and Analysis
FRP	Forest Response Program
IFS	Integrated Forest Study
MCCP	Mountain Cloud Chemistry Program
MPO	Major Program Output
NADP/NTN	National Atmospheric Deposition Program/National Trends Network
NAPAP	National Acid Precipitation Assessment Program
NCASI	National Council of the Paper Industry for Air and Stream Improvement, Inc.
NCLAN	National Crop Loss Assessment Network
NEDS	National Emissions Data System
OTC	Open-top chamber
QAPP	Quality Assurance Project Plan
QA	Quality Assurance
QC	Quality Control
ROPIS	Response of Plants to Interactive Stress
S&I	Synthesis and Integration
SC	Southern Commercial
SF	Spruce-Fir
TSA	Technical system autdit
TVA	Tennessee Valley Authority
USDA	United States Department of Agriculture
USFS	USDA Forest Service
VS	Vegetation Survey
WC	Western Conifers
WMP	Watershed Manipulation Project

7.4 Appendix D: Scientific Names of Trees

American beech	*Fagus grandifolia* Ehrhart
Balsam fir	*Abies balsamea* (Linnaeus) Miller
Black cherry	*Prunus serotina* Ehrhart
Black spruce	*Picea mariana* (Mill.) B.S.P.
Douglas-fir	*Pseudotsuga menziesii* (Mirbel) Franco
Engelmann spruce	*Picea engelmanni* Parry
European beech	*Fagus sylvatica* Linnaeus
Fraser fir	*Abies fraseri* (Pursh) Poiret
Honey locust	*Gleditsia triacanthos* Linnaeus
Jeffrey pine	*Pinus jeffreyi* Greville and Balfour
Loblolly pine	*Pinus taeda* Linnaeus
Lodgepole pine	*Pinus contorta* Loudon
Norway spruce	*Picea abies* (Linnaeus) Karaten
Ponderosa pine	*Pinus ponderosa* Douglas
Red maple	*Acer rubrum* Linnaeus
Red oak	*Quercus rubra* Linnaeus
Red Spruce	*Picea rubens* Sargent
Shagbark hickory	*Carya ovata* (Miller) K. Koch
Shortleaf pine	*Pinus echinata* Miller
Slash pine	*Pinus elliottii* Engelm. var.elliotii
Subalpine fir	*Abies lasiocarpa* (Hooker) Nuttall
Sugar maple	*Acer saccharum* Marsh
Sweetgum	*Liquidambar styraciflua* Linnaeus
Trembling aspen	*Populus tremuloides* Michaux
Western hemlock	*Tsuga heterophylla* (Rafinesque) Sargent
western red cedar	*Thuja plicata* Donn
White ash	*Fraxinus americana* Linnaeus
White fir	*Abies concolor* (Gordon & Glendinning) Lindley
White oak	*Quercus alba* Linnaeus
Yellow birch	*Betula alleghaniensis* Britton
Yellow-poplar	*Liriodendron tulipifera* Linnaeus

7.5 Appendix E: Summary Tables of FRP Research

Table 4. Seedling responses to controlled exposures of pollutants (see legend at end of table).

Southern pines

SOURCE	SPECIES	TREATMENT[1]			RESPONSE[2]														
					Foliage				Stem						Root		Ps		Other
		Duration	O_3 ppb range (# levels)	pH range (# levels)	cond.		mass		mass		ht.		dia.						
					O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	
McLaughlin et al. SC04-1 (lab)	loblolly pine	12 wks	0 - 320 (3)				0		0		+		0		-		-		0 foliar nutrients
(field)	loblolly pine	12 wks	CF - A + 160 A = 38 (5)	3.3 - 5.2 (3)			0	0	0	0	* - 0 +		+ - 0	0	-	0	-	+	O_3: - foliar nutrients - mycorrhizal infection - C allocation to roots pH: + foliar Al 0 stomatal conductance due to O_3
Reinert et al. SC05-5 (lab)	loblolly pine	13 wks	0 - 320 (5)				-		-		-		-						
Reinert et al. SC05-1 (lab)	loblolly pine	13 wks	0 - 320 (5)	3.3 - 5.3 (3)			-	0	-	0	-	0	-	0	-	0			O_3: ↑ foliar N (greatest at 160 ppb) ↓ foliar starch
Kress et al. SC06-3 (field)	loblolly pine	8 mo/yr 2yrs	CF - 3A A = 48 (5)	3.5 - 5.2 (2)	-	0	-	0	-	0	-	0	-	+	-				enhanced growth at 1.5 x ambient O_3 vs ambient concentrations
Richardson & Sasek SC07-6 (field)	loblolly pine	8mo/yr 2 yrs	CF - 3A A = 48 (5)	3.5 - 5.2 (2)													-	0	Same seedlings used by Kress et al. SC06-3
Reardon et al. SC12-1 (field)	shortleaf pine	12 mo	CF - 2.5A A = ? (4)	3.3 - 5.3 (3)			-	-	0	0									O_3: + needle glucose - needle starch + needle protein
Flagler SC14 pers. comm. (field)	shortleaf pine	16 mo	CF - 2.5A A = 40.5 (4)	3.3 - 5.3 (3)	-	0	-	0	-	0	-	0	-	0			-	+	O_3: -chlorophyll content - needle area pH: 0 chlorophyll content 0 needle area

continued

Table 4, continued. (see legend at end of table)

Southern pines

SOURCE	SPECIES	TREATMENT[1]			RESPONSE[2]														
					Foliage				Stem						Root		Ps		Other
					cond.		mass		mass		ht.		dia.						
		Dura-tion	O_3 ppb range (# levels)	pH range (# levels)	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	
Dean & Johnson SC13 pers. comm. (field)	slash pine	7 mo	CF - 3.0A (4) A = 33	3.3 - 5.3 (3)							-	+	-	+	0	+			+ stem vol. due to acid - stem vol. due to O_3 root data (root-length density) reflects 1 year of exposure
Wiselogel et al. SC02-1 (lab)	loblolly pine	9 wks	CF-CF + 320 (3)		-				-		-		-		-		-		0 sugar and starch content of roots + sugar to starch ratio in roots
Wiselogel et al. SC02-2 (lab)	loblolly pine	12 wks	CF-CF + 320 (2)		-		-		-		-		-		-				response of 12 wk old seedlings and 1 yr old seedlings are fairly similiar
Wright et al. SC15-6 (field)	loblolly pine tolerant family	7 mo	CF - 2.5A (4) A = 40	3.3 - 5.3 (3)			0	+	+	+	+	+	0	+					2 genetic families tested. O_3: + stem N ↑ N retranslocation to stem due to ↑ senescence of foliage
	sensitive family						-	+	0	+	-	+	-	+					
Chappelka et al. SC15-7 (field)	loblolly pine tolerant family	16 mo	CF - 2.5A (4) A = 40	3.3 - 5.3 (3)	-	0	-	+			-	+	0	+			-	0	Same seedlings as Wright et al. Sensitive family vs. tolerant family: greater visible injury greater reduction in Ps
	sensitive family				-	0	-	+			-	+	-	+			-	0	

continued

Table 4, continued. (see legend at end of table)

Western conifers

SOURCE	SPECIES	TREATMENT[1]			RESPONSE[2]																
		Duration	O_3 ppb range (# levels)	pH range (# levels)	Foliage				Stem						Root		Ps		Other
					cond.		mass		mass		ht.		dia.						
					O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	
Hogsett & Tingey WC08-1 (field) see also: Hogsett et al. WC08-2	Douglas-fir	4,2 mo/yr 2yrs		2.1 - 5.6 (3)		0		0		+		+		+		-			Duration of exposure are 4 mo. of O_3 in summer followed by 2 mo. of acid fog in the winter
	ponderosa pine					0		0		0		+		0		0			
	Douglas-fir	4,2 mo/yr 2yrs	CF - 71[220] ave[peak] (3)	2.1 - 5.6 (3)	0	0	-	-	0	0	0	0	0	0	0	0			Measurements are taken during growth season following exposure
	ponderosa pine				-	0	-	0	-	0	-	0	-	0	-	0			Second-year observations generally agree with first year except lodgepole pine showed reduced root and foliage mass due to O_3
	western hemlock				-	-	-	0	-	0	-	0	0	0	-	0			
	western red cedar				0	-	-	+	0	+	+	0	0	0	0	-			Ponderosa pine & western hemlock most sensitive to O_3
	lodgepole pine				-	0	0	0	0	0	0	0	0	0	0	0			Western red cedar least sensitive to O_3

continued

Table 4, continued. (see legend at end of table)

Western conifers

SOURCE	SPECIES	TREATMENT[1]			RESPONSE[2]														
					Foliage				Stem						Root		Ps		Other
		Duration	O_3 ppb range (# levels)	pH range (# levels)	cond.		mass		mass		ht.		dia.						
					O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	
Miller et al. WC09-1,3 1988 results (field)	white fir	3, 2 mo/yr 2 yrs	CF - 71[220] (4)	2.1 - 5.6 (3)	-	-	-	0	0	0	+	+	0	0	0	-			Exposures are similiar to Hogsett and Tingey WC08-1 Considerable variability in seedling response between 1988 and 1989 exposures.
	subalpine fir				-	-	-	-	0	-	0	+	0	0	0	-			
	Engelmann spruce				0	0	+	+	+	+	0	0	0	+	+	0			
	ponderosa pine				-	-	-	+	-	0	0	-	-	+	-	-			
	Douglas-fir				0	-	0	+	-	+	+	+	0	+	-	-			
1989 results (new seedlings) (field)	white fir				-		+	+	+	-	+	+	0	+	+	0			
	subalpine fir				-		+	-	+	0	0	+	+	0	0	-			
	Engelmann spruce				0		-	0	0	0	-	-	-	-	0	+			
	ponderosa pine				-		0	0	0	0	+	+	+	+	0	0			
	Douglas-fir				-		0	-	+	-	-	0	+	-	0	-			

continued

Table 4, continued. (see legend at end of table)

Western conifers

SOURCE	SPECIES	TREATMENT[1]			RESPONSE[2]														Other
					Foliage				Stem						Root		Ps		
		Duration	O_3 ppb range (# levels)	pH range (# levels)	cond.		mass		mass		ht.		dia.						
					O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	
Turner et al. WC07-1 (field)	Douglas-fir	2 mo		2.1 - 5.6 (3)		0		0								0			Growth responses are derived from Hogsett & Tingey's (WC08-1) seedlings
	ponderosa pine					0		0								0			- root-to-shoot ratio
	western hemlock					-		0								-			Douglas-fir tested for foliar leaching in a lab study:
	western red cedar					-		+								0			+ foliar leaching of K, Ca, Mg 0 foliar content of K, Ca, Mg

continued

Table 4, continued. (see legend at end of table)

Eastern spruce and fir

SOURCE	SPECIES	TREATMENT[1]			RESPONSE[2]														
					Foliage				Stem						Root		Ps		Other
		Duration	O_3 ppb range (# levels)	pH range (# levels)	cond.		mass		mass		ht.		dia.						
					O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	
Jacobson et al. SF06-1,2 (lab + field)	red spruce	6 - 19 wks		2.5 - 4.5 (3)		- w SO_4				-		- +		0		- w NO_3			- foliar K, Ca, Mg + foliar N w/NO_3 at low pH + foliar S w/ SO_4 at low pH ↑ foliar injury w/ low N to roots
Patton et al. SF07-2 (lab)	red spruce	6 mo	CF - 150 (3)	3.5 - 4.5 (3)	0	0	0	0	0	0	0		0	0	0	0			current-yr needles: O_3: + carbohydrates, P - Cu pH: + Ca
Patton et al. SF07-1 (lab)	red spruce	6 mo	50 - 150 (3)	3.0-4.2 (2)	0			-		-			+	-		-			O_3: + thrufall Mg, Mn, B, and Na pH: * w/H_2O freq. + thrufall Fe, Mn - thrufall B, Mg, Na
Seiler & Chevone SF13-4 (lab)	Fraser fir	10 wks	< 20 - 100 (3)																0 needle water potential, osmotic potential, and turgor potential
Seiler et al. SF13-1 (lab)	Fraser fir	10 wks		3.0 - 5.6 (3)						-†						0		0	? needle conductance and transpiration
Tseng et al. SF13-2 (lab)	Fraser fir	10 wks	< 20 - 100 (3)						0				0		0		-		

continued

Table 4, continued. (see legend at end of table)

Eastern spruce and fir

SOURCE	SPECIES	TREATMENT[1]			RESPONSE[2]														
		Duration	O_3 ppb range (# levels)	pH range (# levels)	Foliage cond.		Foliage mass		Stem mass		Stem ht.		Stem dia.		Root		Ps		Other
					O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	
Cape et al. SF14-4 (field)	red spruce	21 wks		2.5 - 5.0 (6)															- frost hardening
Leith et al. SF14-6 (field)	red spruce	22 wks		2.5 - 5.0 (6)		-													
Neighbour & Melhorn SF14-16 (lab)	red spruce	4 mo/yr 2 yrs	CF - CF + 70 (4)																- frost hardening NO removal reduces O_3 effect
Chen & Wellburn SF14-7 (field)	red & Norway spruce	6 mo (rs) 3 mo (Ns)		2.5 - 5.0 (6)		-													+ stress ethylene emission rate
Eamus & Fowler SF14-9 (field)	red spruce	6 mo		2.5 - 5.0 (2)														+	+ stomatal conductance due to acidity
Eamus et al. SF14-8 (field)	red spruce	3 mo		2.5 - 5.0 (6)															0 transpiration and cuticular resistance - shoot H_2O potential, maximum turgor, and relative H_2O content
Alscher et al. SF16-5 (field)	red spruce	6 mo	CF - 2A A = 40 (4)						0						0				0 non-structural carbon in foliage and roots 0 electron transport rate 0 foliar pigments delayed production of raffinose
Cumming et al. SF16-2 (field)	red spruce	16 wks	CF - 3A A = 40																+ electron transport rate† and respiration - photosynthetic pigments

continued

Table 4, continued. (see legend at end of table)

Eastern spruce and fir

SOURCE	SPECIES	TREATMENT[1]			RESPONSE[2]														Other
					Foliage				Stem						Root		Ps		
		Duration	O_3 ppb range (# levels)	pH range (# levels)	cond.		mass		mass		ht.		dia.						
					O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	
Fincher et al. SF16-4 (field)	red spruce	7 mo	CF - 3A A=40 (4)		-														- mesophyll cell condition following frosts - photosynthetic pigments
Laurence et al. SF31-2 (field)	red spruce	3 mo	0.5A - 2A A=38 (4)	3.1 - 5.1 (3)			0	0	+†	0	0	0			+†	0	-†	0	+ & - responses were not statistically significant (see text)
Kohut et al. SF31-1 (field)	red spruce	4 mo	0.5A - 2A A=38 (4)	3.1 - 5.1 (3)			0	0	0	0							0	+	Second year of exposures of seedlings used by Laurence et al. SF31-2
Thornton et al. SF27-3 (field)	red spruce	13 wks	CF - A (2)	mist filter -A (2)	0	0			0	0			0	0	0	0	0	0	Ambient clouds on Whitetop Mt. filtered w/B-GON mist filter Native seedlings not affected, commercial seedlings (Phyton) showed enhanced Ps w/pollutant exclusion (not statistically significant)
Deans et al. SF14-19	red spruce	22 wks		2.5-5.0 (6)															+ root branching - partitioning to coarse roots - mycorrhizal fruiting bodies

continued

Table 4, continued. (see legend at end of table)

Eastern hardwoods

SOURCE	SPECIES	TREATMENT[1]			RESPONSE[2]														
					Foliage				Stem						Root		Ps		Other
		Duration	O_3 ppb range (# levels)	pH range (# levels)	cond.		mass		mass		ht.		dia.						
					O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	
Davis & Skelly EH01-1 (lab)	black cherry	12 wks	0-150 (3)	3.0 - 4.2 (2)	-	0	-	-	-	-		-							some interaction of pH and O_3 on foliar injury
	sweetgum				-	0	0		0										
	yellow-poplar				-	0	0		0										no consistent demonstrable effect of pH on growth of any species other than black cherry
	white ash				-	0	0		0										
	yellow birch				-	0	-		-										
	red maple				-	0	-		-										
	white oak				-	0	-		-										
	red oak				0	0	0		0										

continued

Table 4, continued. (see legend at end of table)

Eastern hardwoods

SOURCE	SPECIES	TREATMENT^1			RESPONSE^2														
		Duration	O_3 ppb range (# levels)	pH range (# levels)	Foliage				Stem						Root		Ps		Other
					cond.		mass		mass		ht.		dia.						
					O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	
Jensen & Dochinger EH06-1 (lab)	white ash	16 wks	0-150 (3)	3.0 - 4.2 (3)	-	0	-	-	-	-									
	yellow birch				-	0	-	-	-	+									
	sweetgum				-	0	0	+	0	+									
	sugar maple				0	0	-	-	-	-									
	yellow-poplar				-	0	0	0	0	0									
	red maple				-	0	-	+	0	0									
	white oak				0	0	0	0	0	0									
	shagbark hickory				0	0	0	0	0	0									
	American beech				0	0	0	0	0	0									
	European beech				0	0	0	0	0	0									

continued

Table 4, continued. (see legend at end of table)

Eastern hardwoods

SOURCE	SPECIES	TREATMENT[1]			RESPONSE[2]																
					Foliage				Stem						Root		Ps		Other
		Duration	O_3 ppb range (# levels)	pH range (# levels)	cond.		mass		mass		ht.		dia.						
					O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	O_3	pH	
Foster et al. EH06-2 (lab)	white oak	18 mo 20 wks/yr 2 yrs	0 - 150 (2) 1st yr; 0-1.15A (2) 2nd yr														0		0 quantum efficiency 0 carboxylation efficiency 0 respiration 0 stomatal conductance
Karnosky et al. EH03-5 (field) see also EH03-1	trembling aspen	3 mo	CF - 80 (3)		-		-		-		-		-		-				

LEGEND

[1] Treatment symbols:

A = ambient concentration
CF = charcoal filtered

[2] Symbols represent the seedlings' response relative to the control or nominal treatment:

0 = no effect
- = negative effect or suppression
+ = positive effect or enhancement
* = treatment interaction
† = our interpretation(different from author's)

Note: blank cells indicate response not measured

Abbreviations:

ppb = parts per billion
cond = visible condition
ht. = height
dia. = diameter
Ps = photosynthesis
wks. = weeks
SC = Southern Commercial Research Cooperative
WC = Western Conifer Research Cooperative
SF = Spruce-Fir Research Cooperative
EH = Eastern Hardwoods Research Cooperative

Table 5. Soil/Nutrient Cycling Studies

SOURCE	STUDY MATERIAL & SITE CHARACTERISTICS	VARIABLES OF INTEREST	ASSOCIATED VARIABLES	RESULTS
Binkley et al. SC16-1	Soils sampled in 1962 and 1982 in a cotton field converted to loblolly pine in 1957; Calhoun Experimental Forest, SC	Soil: pH extractable cations titratable acidity titratable alkalinity	Time	Over 20 years: ↓ pH by 0.3 to 0.8 units in all horizons marginal ↓ in titratable alkalinity and marked ↑ in titratable acidity ↓ extractable Ca, Mg, & K by 20-80% ↑ extractable Al by 10-60% **Most cation loss probably due to accumulation in biomass; changes in soil chemistry may be induced by land-use changes**
David et al. VS10-7	Soil and forest floor in 5 locations in each of 169 plots across MN, WI, MI	Soil and forest floor: C N S	SO_4 deposition Relative location Forest type	C, N, and S concentrations in the forest floors and mineral soil not very different across gradient Balsam fir stands had ↑ S in forest floor **S, after adjusting for N, was 15% greater in forest floors and mineral soil at eastern high deposition plots**
Fernandez & Lawrence SF04-1	Nutrient fluxes in spruce-fir forest; Howland Site, ME	Chemistries: soil solution throughfall precipitation stemflow Litter Biomass Foliage		Precipitation neutralized by contact with foliage Cations and organic acids leached from foliage No evidence of N saturation based on foliar chemistry **Precipitation chemistry is modified by foliage**
Grigal & Ohmann VS10-3	Forest floor at 5 locations in each of 171 plots across MN, WS, MI	Forest floor: P cations heavy metals	SO_4 deposition Relative location	West to east: ↓ Ca, Mg, K, Na; ↑ Pb, Cd; no change in Cu, Zn; Ni differences but no pattern **Trends consistent with atmospheric deposition of Ca, Mg, K, Na, and P from western soil-derived sources and deposition of Pb and Cd from eastern anthropogenic sources**
Huntington et al. SF05-7	Red spruce stands at varying elevations and aspects; Mt. Moosilauke, NH	Tree foliage Crown condition Soil chemistry Forest floor chemistry	Cryofolist soils Spodosol soils Elevation Aspect	With ↑ crown vigor: ↑ soil P, forest floor exchangeable Mg & Ca ↑ exchangeable soil Ca with ↑ foliar Ca Foliar element concentrations not correlated with crown vigor **Red spruce do not appear to be deficient in foliar nutrients with the possible exception of P**
Huntington et al. SF30-1	Soil solution in hydrologically isolated soil blocks; Whiteface Mtn., NY	Soil Solution Chemistry: rapidly reactive (RR) Al anions	Simulated SO_4 deposition Precipitation of pH 3.5, 4.5, 5.1	RR Al ↑ with anion concentration; highest just below forest floor Unrealistic N mineralization with soil block isolation may influence results **RR Al in soil solutions considerably less than 'harmful' (200 μM/L) concentration**

continued

Table 5. Soil/Nutrient Cycling Studies (continued)

SOURCE	STUDY MATERIAL & SITE CHARACTERISTICS	VARIABLES OF INTEREST	ASSOCIATED VARIABLES	RESULTS
Huntington & Ryan SF05-6	Soils sampled on east aspects at 840, 1000, and 1200m; Mt. Moosilauke, NH	Soil and forest floor: extractable cations Al P	Elevation Soil type	With ↑ elevation: ↑ occurrence of cryofolists, ↓ spodosols ↑ soil mass in cryofolists in spodosols: forest floor: ↓ Ca, Mg, K, base saturation, ↑ Al, ?P mineral soil: ↓ Ca, Mg, base saturation, ↑ Al, K, P in cryofolists: forest floor: ↓ Ca, Mg, P, base saturation, ? Al, K mineral soil: ↓ Ca, Mg, K, Al, P, base saturation **Trends associated with elevation within soil types** **No difference between soils on east vs. west aspect**
Johnson et al. SF08-4	Soils and 69 red spruce trees on NW aspect at 700 and 1300 m; Whiteface Mtn., NY	Foliar chemistry Crown vigor Soil chemistry	Elevation	↓ foliar K with ↓ crown vigor; foliar Ca & Mg not correlated with crown vigor Sufficient foliar Ca and K; foliar Mg moderately deficient No correlation between soil & foliar levels of K, Ca, Mg, or Al With ↑ elevation: ↓ foliar & soil Mg, soil Ca; ↑ soil K & Al **Relatively low soil cations do not limit foliar content**
Johnson et al. SF08-14	Forest floor and soil at 56 plots in hardwood-spruce and fir-spruce zones on all aspects from 700-1200 m; Whiteface Mtn., NY	Soil: exchangeable nutrients pH depth Al Forest floor pH	Red spruce mortality	**No indication that soil depth, soil pH, forest floor pH, and exchangeable Ca, Mg, K, and Al are correlated with crown damage**
Joslin et al. SF27-1	Nutrient fluxes and tree condition in 2 red spruce stands at summit that differ in atmospheric inputs Whitetop Mtn., VA	Chemistries: throughfall stemflow soil solution bulk soil foliage Foliar injury Stem elongation Litterfall	SO_4 deposition Cloud water deposition	High-cloud deposition vs. low-cloud deposition site: solution flux to the forest floor was 15%, 29%, and 45% greater for SO_4 NO_3, and NH_4, resp. ↓ foliar growth, bud mortality, and needle retention only evidence for ↑ winter damage was slightly ↑ litterfall, probably from wind and ice ↓ foliage concentrations of Mg, Zn, Ca ↑ foliage concentrations of K and B soil solution dominated by NO_3 and responsible for fluctations in Al conc. **High N deposition may be inducing toxic Al concentrations in soil**
Joslin et al. SF27-5	Cloud-water generated throughfall from red spruce saplings at 1700 m summit; Whitetop Mtn., VA	Throughfall chemistry	Cloud water deposition	Relative importance of cations shifts as cloud water becomes throughfall: ↓ H to 2/3, NH_4 to 1/3 of original contribution ↑ K, Na, Mg, Ca at least 100% ↑ Ca by 18-fold and Mg by 25-fold as cloud water pH ↓ from 4.6 to 2.9 Relative importance of major anions (SO_4, NO_3, Cl) remained relatively constant **Acidic cloud water may contribute to nutrient deficiencies on nutrient-poor sites**

continued

Table 5. Soil/Nutrient Cycling Studies (continued)

SOURCE	STUDY MATERIAL & SITE CHARACTERISTICS	VARIABLES OF INTEREST	ASSOCIATED VARIABLES	RESULTS
Loucks & Somers EH05-6	Soil in oak-hickory forest; 7 sites; 8 plots/site; along a gradient of acid deposition; AR to OH	Soil: pH C S	Soil type Elevation Aspect	↓ soil pH from west to east High C in A_1 horizon in eastern states Increasing soils from west to east **High SO_4 deposition may be inhibiting soil C decomposition**
Ludovici et al. SC05-8 (co-funded by NCASI)	Soils (clayey, mixed, thermic aquic Hapludult) in pots, planted with loblolly pine seedlings, exposed to simulated acid rain. 3 applications/wk for 20 wks. Piedmont, NC	Soil: pH %base saturation (%BS) %Ca (%BS) %Mg (% of BS) CEC (cmol/kg)	pH of simulated acid rain (3.3 vs 4.3) Ratio of S:N of simulated acid rain	pH 3.3 vs 4.3: ↓ %BS (27.9 vs 31.3) ↓ %Ca (21.4 vs 24.0) ↓ %Mg (5.2 vs 5.8) ↓ %pH (4.49 vs 4.57) ↑ CEC (3.39 vs 3.00)
McCormick EH04-3	Nutrient content in sap of red maple trees at 7 sites along a deposition gradient Pennsylvania	Sap chemistry: pH conductivity specific ions	Atmospheric deposition Soil chemistry	Large tree-to-tree variation in sap chemistry **Positive relationship observed between sap concentration atmospheric deposition and Ca, and soil exchangeable concentrations of Mg and of Ca**
Robarge & Smithson SF12-2	Small-scale spatial variability of soil chemical parameters; Roan Mtn., NC	Soil: pH extractable cations titratable acidity extractable sulfate N and C		Within-plot variability (12x14m) for most soil chemical parameters is high: > 30% coefficient of variation Variability generally remains constant with soil depth Expressing results on a mass per unit area basis increases variablity Expressing results as a ratio decreases variability **Assessment of between-plot and within-plot variability in the southern Appalachian Mtns. suggests minimum detectable differences of > 10% for soil chemical parameters over time across all plots** **Detecting differences in single plots over time is probably not possible without extensive sampling per plot**
Ryan & Huntington SF05-8	Soil sampled on west aspects at 840, 1000, and 1200 m; Mt. Moosilauke, NH	Soil and forest floor: extractable cations Al	Soil type Elevation	With ↑ elevation: ↑ occurrence of cryofolists, ↓ spodosols ↓ soil mass in both soil types in spodosols: forest floor: ↓ Ca, Mg, K, base saturation, ↑ Al mineral soil: ↓ Ca and base saturation, ↑ Mg, K, ?Al in cryofolists: forest floor: ↓ Ca, Mg, K base saturation, ↑ Al mineral soil: ↓ Ca, Al, ↑ Mg, K, base saturation **Trends associated with elevation within soil types**

continued

Table 5. Soil/Nutrient Cycling Studies (continued)

SOURCE	STUDY MATERIAL & SITE CHARACTERISTICS	VARIABLES OF INTEREST	ASSOCIATED VARIABLES	RESULTS
Sasser and Binkley SF17-2	2 fir waves: Fraser fir on Mt. LeConte, Great Smoky Mtns. National Park (1900 m, NE slope); balsam fir on Whiteface Mtn, NY (1200m, S slope)	Net N mineralization Throughfall	Forest type Forest zone (dead, mature, regeneration, juvenile)	Net N mineralization: Dead and mature zones showed twice the rates of regenerating of juvenile zones (43-61 vs. 21-39 kg N/ha/yr) Throughfall ranged from 4-10 kg N/ha/yr across all zones at both sites. 75% of throughfall N was NH_4 for both site **N mineralization similar between mountains and relatively high at all stages of stand development**
Smithson et al. SF12-7	Soil solution from field lysimeters installed in 1986; Mt. Mitchell, NC Whitetop Mtn., VA	Soil solution: pH Al, Ca, Mg, K, Na, NH_4, NO_3, SO_4, Cl	Season Elevation at Mt. Mitchell (2006 vs 1760m) Location: (Mt. Mitchell vs Whitetop)	Soil solution from high elevation at Mt. Mitchell is slightly more concentrated in H, Al, and SO_4 than low elevation, however differences are not statistically significant. Soil solution from Whitetop Mtn. more concentrated than solutions from Mt. Mitchell Seasonal variation in soil solution highly significant, especially for NO_3, Al, Ca and Mg Al and NO_3 are dominant ions in solution SO_4 is accumulating in rooting zone. There is a net export of NO_3 and possibly Mg (estimated to be 25 and 1 kg/ha/yr, resp. at Mt. Mitchell) **Al in soil solution at Mt. Mitchell is generally less than 'harmful' (200 μM) concentration. A larger number of samples had >200 μM Al concentration at Whitetop Mtn.**
Smithson & Robarge SF12-6	Leachate from Oa, A, B horizons collected near MCCP study site and exposed to simulated throughfall in a lab study; same sites as those used by Smithson et al. SF12-7 Mt. Mitchell, NC Whitetop Mtn., VA	Leachate solution: pH Al, Ca, Mg, K, Na, NH_4, NO_3, SO_4, Cl	Simulated throughfall: pH: deionized H_20 1x throughfall 2x throughfall ionic strength: 1x throughfall (created using K salts) Storage conditions time (12 wks) 4°C	Solution concentrations of leachate increased with decreased pH of throughfall; acid and salt treatments of equal ionic strength have same effect; Ca, Mg dominant cations; Al concentrations < 100 μM; no change in pH; proton consumption equal to SO_4 adsorption not metal ion release; relative sensitivity to leaching: Oa > A > B horizon Storage at 4 °C does not inhibit NO_3 formation; NO_3 release is immediate following soil disturbance and lowers pH and increases Al concentration in soil solution **Acidic inputs via throughfall can cause short term changes in soil solution composition. Short-term changes are dominated by base cations, not Al.**
Strader et al. SF17-1	Red spruce and Fraser fir in 3 high-elevation sites (19 plots) ranging in elevation from 1579-2006 m; Mt. Mitchell, NC; Clingmans Dome, GSMNP; Whitetop Mtn, VA,	N mineralization rates in situ Throughfall N	Elevation Aspect	N content of throughfall was high, (18-32 kg N/ha/yr) indicating substantial atmospheric deposition N mineralization rates were high (26 to 180 kg N/ha/yr) NO_3 accounted for approximately 50% of total mineralized N on Clingmans Dome and 40-50% on Whitetop Mtn. **Rates of N mineralizations were thought to be equalled by vegetation uptake. If not, potential exists for cation leaching**

continued

Table 5. Soil/Nutrient Cycling Studies (continued)

SOURCE	STUDY MATERIAL & SITE CHARACTERISTICS	VARIABLES OF INTEREST	ASSOCIATED VARIABLES	RESULTS
Wells et al. SF21-4	Foliar and soil samples from 115 permanent plots and root samples from 30 plots in the spruce-fir forests of the southern Appalachians at elevations of 1525, 1678, 1952m Mount Rogers, VA Black Mountains, NC Clingmans Dome, TN	Foliar and root concentrations: N, P, K, Ca, Mg, Cu, Fe, Mn, Zn, Pb, S, B, Sr, Ni, Cd Soil: pH (in water), extractable cations, titratable acidity, extractable sulfate, extractable metals total N and C	Location Elevation Topographic position(draw, slope, ridge) Exposure(exposed slopes: north and west; protected: east and south) GSMNP,	Foliar concentrations: similiar for three locations; Ca and Mg near critical range; N and K may be excess; P, S, Cu, Fe, Mn sufficient; ? Zn **Red spruce do not appear to be deficient in foliar nutrients except for Ca and Mg; Al is high and increases with elevation.** Soil: Oi & Oe layer , mean(s.d.): pH = 3.9 (0.32); base saturation = 35 (16); Ca: Al = 2.45 (5.02) 15-20 cm depth, mean(s.d.): pH = 4.3 (0.32); base saturation = 7.3 (7.0); Ca: Al = 0.035 (0.035) pH, Ca, K, base saturation vary by location not elevation; Mg ↓ with elevation; Al, titratable acidity vary by topographic position; Pb > on west aspects then on east aspects; total mass of Ca and Mg ↓ with elevation; total mass of Pb, S, N, K ↑ with elevation **Highly significant elevation-location interaction for most soil parameters. Within plot variability limits ability to detect significant trends.**
Witter et al. EH03-7 Pregitzer et al. EH03-4 Liechty and Mroz EH03-3	Nutrient cycling in sugar maple-hardwood forest at 5 sites; 3 plots/site; along a gradient from ne MN to sw MI	Mass fluxes between and contents in: foliage forest floor (Oi), (Oea) woody biomass soil A & E horizon soil B horizon	SO_4 deposition NO_3 deposition Relative location	With ↑ SO_4 and N deposition along gradient from northwest to southeast: ↑ S contents in foliage and in litter (Oi), related to ↑ mass of Oi ↑ S fluxes in litterfall and in soil leachate ↑ N contents in litter (Oi), related to ↑ mass of Oi 0 foliar contents of N, Ca, Mg, K (Ca & Mg related to soil) Nutrient contents in soils follow soil organic matter trends except S, which follows deposition of SO_4 Nutrient leaching below B horizon is greater than wet & dry deposition for SO_4, Ca, Mg, and K; only SO_4 follows deposition trend of SO_4 Ca losses below B horizon > literature estimates of mineral weathering Cations (Ca, Mg) fluxes in throughfall are at least weakly correlated with deposition of SO_4 **Nutrient cycling rates and pools are correlated with deposition trends of SO_4, N, and H**

Table 6. Root Studies

SOURCE	STUDY MATERIAL & SITE CHARACTERISTICS	VARIABLES OF INTEREST	ASSOCIATED VARIABLES	RESULTS
Wargo et al. SF15-1	21 red spruce co-dominant trees in 3 decline classes at 950 m; Mt. Abraham in Green Mountain National Forest, VT	Roots: mycorrhizae pathogen isolation vitality chemistry	Crown characteristics (class 1, 2, and 3: 0-10%, 10-50%, 50-100% crown deterioration, respectively) Increment cores Branch condition	Class 2 and 3 trees showed greater radial growth reductions than class 1 trees Declining trees had root decline symptoms: fewer non-woody fine roots, fewer mycorrhizal tips, fewer morphological types of mycorrhizae, greater discoloration, greater amounts of dead tissue, lower starch, lower soluble carbohydrates, and lower soluble N concentrations While some pathogenic fungi have been isolated, none of the "common" root rot fungi have been isolated to date Patterns of root and crown deterioration suggest that fine roots deteriorate first, followed by deterioration of crown condition, finally followed by woody root death **Decline in crown conditions of red spruce may be caused by a declining root system**
See also: Smith and Armstrong-Colaccino SF05-12 Table 7 Cline et al. SC09-1 Table 11 Seedling studies Table 4				

Table 7. Forest Condition Studies

SOURCE	STUDY MATERIAL & SITE CHARACTERISTICS	VARIABLES OF INTEREST	ASSOCIATED VARIABLES	RESULTS
Brubaker WC25-1	Increment cores from 13 old-growth Douglas-fir sites; 12 sites are in the Puget Sound area, 1 in the H.J. Andrews Exp. Forest, OR	Annual tree ring width over time	Monthly precipitation and temperature records from nearby weather stations	Overall radial growth increases since 1880; likely related to a regional temperature increase. **No growth patterns appear related to pollution sources**
Bruck et al. SF02-5	Four annual surveys of forest condition conducted in 16 plots, 272 red spruce and 213 fraser fir were assessed Mt. Mitchell, NC	Foliage loss Live vs. dead	Time (1984-1987)	Crowns of both red spruce and Fraser fir deteriorated over time By 1986 7% of red spruce and 16% of Fraser fir had died, after winter of 1986-87 41% of red spruce and 49% of Fraser fir had died No causal biotic agents observed **Abrupt increase in mortality is thought to be due to drought and severe rime ice**
Conkey & Keifer SF05-13	Increment cores from 20 red spruce and 10 balsam fir at each of 6 sites on east and west aspects at 840, 990, and 1140 m; Mt. Moosilauke, NH, and Northeastern US	Growth rate	Aspect Elevation Species Time	Growth increases in 1900 & 1940; a radial growth reduction beginning about 1955 Patterns similar for balsam fir and red spruce No greater decline on west slope or with ↑ elevation **Recent decline not clearly related to pollution, may be related to climate change**
Dull et al. SF26-1	Aerial photos and ground surveys via Geographic Information Systems (GIS); southern Appalachians	Red spruce and fraser fir cover typing and standing dead estimates	Mt. range Elevation Balsam woolly adelgid occurrence	Fraser fir standing dead ranges from 44% on Roan Mtn. to 91% in the Great Smoky Mountains Red spruce standing dead ranges from 3% on Roan Mtn. to 14% in the Black Mtns. Fraser fir standing dead increases with elevation **Fraser fir standing dead is highly correlated with the presence of historical adelgid infestation; red spruce standing dead is not higher than expected**
Federer et al. VS06-12	Increment cores of 3001 red spruce from broad survey of four northeastern states; ME, NH, VT, NY	Basal-area increment over time	Monthly precipitation and temperature records from nearby weather stations	High frequency variation of basal-area growth negatively correlated with previous year summer temperature (July & August), and positively correlated with early winter temperatures No change in growth/climate relationship since 1960 **Suggests a regional climate signal for red spruce**
Federer & Hornbeck VS06-3	Increment cores of 3001 red spruce from broad survey of four northeastern states; ME, NH, VT, NY	Average annual basal area increment	Stand age and stand density as interpolated from Myer's normal yield tables.	Mean basal area increments increased until the early 1960's and have decreased since **Maturation of stands throughout New England suggested as a possible cause**

continued

Table 7. Forest Condition Studies (continued)

SOURCE	STUDY MATERIAL & SITE CHARACTERISTICS	VARIABLES OF INTEREST	ASSOCIATED VARIABLES	RESULTS
Friedland SF08-17	Forest condition of canopy trees assessed in 48 plots stratified by elevation and aspect on each of 19 mountains in northern Appalachians NY, VT, NH, ME	Live vs. dead	Elevation (950-1100 m) Aspect (w vs. e) Mt. range	Abundance of red spruce varies among ranges (highest in White Mts., lowest in Adirondacks) 42% of red spruce were dead, 13% of other species were dead Greater percent red spruce standing dead in western mountains vs. eastern mountains Percent of standing dead red spruce is higher on west aspects vs. east aspects (except Adirondacks) **Percent of standing dead red spruce increases with elevation (particularly above 1000 m) in the Adirondacks and Green Mts., but not in more easterly mts.; no trend for other species with elevation**
Graybill & Rose WC24-1	Increment cores of 889 stems representing older trees at 41 sites on the Mogollon Rim, AZ & NM, or on several isolated mountains in southeast AZ. Ponderosa pine, Douglas-fir were primary species AZ	Actual radial growth Predicted radial growth using precipitation records	Time Location (northern sites were more distant from sources of air pollution than southern sites)	Actual growth was less than predicted growth for the period of 1951-1986 in 63% of sites in the south and 38% of sites in the north **Reduced growth rates (i.e., below those predicted by precipitation records) may be due to higher precipitation in previous decades, air pollution, and/or increased competition from other stems**
Hornbeck et al. VS06-5	Increment cores of > 5000 co-dominant trees representing existing forest ages, basal area, and stocking levels < 1000 m elevation New England	Annual basal area increment averaged across all factors influencing tree growth	10 different species which comprise 86% of New England forests	Eight species (including sugar maple) had constant or increasing basal area increments (white pine had highest) Red spruce and balsam fir had recent decreases in basal area increments **Maturation of stands is suggested for decreases**
LeBlanc EH05-7	Increment cores from 30 white oak and 30 black oaks at each of 7 sites; AR to OH	Change in individual tree mean BAI and BAI trend between pre- and post- 1960	Tree age Competition data B-horizon Ca:Al ratio	18-33% of black oak and 7-20% of white oak exhibit radial growth reduction at sites with low soil Ca:Al ratios, but no white oak and 5-10% of black oak exhibit growth decline at sites with B-horizon Ca:Al ratio > 0.25 No relationship between growth reduction and tree age or competition **Natural or soil-acidification-induced low Ca:Al ratio may adversely affect white and black oak growth on low nutrient, poorly buffered soils**
Miller-Weeks & Cooke VS14-3	Four annual surveys of co-dominant trees conducted in 80 plots with 50% red spruce or balsam fir. Elevation from 300-1200 m Adirondacks & Tug Hill, NY, White Mt. Nat. For., VT & NH, Mongahela, Nat. For., WV, and Berkshires of MA	Crown condition (assessed visually) Live vs. dead	Time (1985 - 1988)	Overall tree crown conditions have deteriorated since 1985, but only a small % of trees have died Annual mortality appears very low Trees are exhibiting foliage loss but little discoloration Foliage loss attributed to individual branch dieback & mortality

continued

Table 7. Forest Condition Studies (continued)

SOURCE	STUDY MATERIAL & SITE CHARACTERISTICS	VARIABLES OF INTEREST	ASSOCIATED VARIABLES	RESULTS
Pederson & McCune EH05-18	Mortality rates of 177 dead trees (> 20 cm dbh) were determined for the past 20 years at each of 7 sites along a gradient of acid deposition; AR to OH	Decade by decade mortality rates Cause of death for the major species	Relative position on an acid deposition gradient Decade '68 - '77 '78 - '87	Among the 7 sites, mean and range of mortality rates (stems/ha/decade) for all species: 1968-1977: 8.83, 6.25 - 15.62 1978-1987: 17.71, 8.33 - 27.08 Individual mortality rate of Quercus rubra and Carya spp. was greater than Q. alba No apparent differences in cause of mortality between decades **Increased mortality in '78 - '87 versus '68 - '77 ($p = 0.10$)** **No trend in mortality along an acid deposition gradient in either decade**
Peterson et al. WC26-3	Foliar injury and growth measured in 56 ponderosa pine stands (either symptomatic or asymptomatic); Sierra Nevada Mountains, CA	Crown condition growth ring widths vs. time series Temporal and spatial variation in growth especially pre 1950 vs. post 1950	Ozone gradient Symptomatic trees vs. asymptomatic trees	High degree of variation among trees and stands in symptomatic injury and tree growth data. Some regional patterns are apparent. Symptomatic injury data indicates gradient of O_3 induced injury (greatest in southern Sierra Nevada, lowest in north) and that there is a high level of pollutant stress **Individual basal area growth analysis of symptomatic southern sites indicate general ↓ trend of growth since 1950 in areas of high O_3 exposure and injury. It is thought that O_3 injury plays a role in the stress complex**
Peterson & Arbaugh WC26-1	Increment cores from 56 sites of ponderosa pine; 28 sites are on the western edge, 28 sites are on the interior; Sierra Nevada Mountains, CA	Annual tree ring width over time	Monthly precipitation and temperature records from nearby weather stations	No apparent large-scale regional reduction of tree growth in the most recent years There is a suggestion that the more southern western edge sites are growing more slowly than the interior southern sites. **O_3 has been suggested as a possible contributor to growth reductions**
Smith & Armstrong-Colaccino SF05-12	Pathogenic symptoms visually assessed on 189 codominant red spruce trees in 19 plots at stratified locations; 46 red spruce trees destructively sampled for branch and root assessments Mt. Moosilauke, NH	Live vs. dead trees Foliar discoloration and loss Specific symptoms associated w/crown, seedlings, branch, roots	Elevation (824 - 1172 m) Aspect (w & e) Soil type (histosols vs. spodosols)	Percent standing dead of red spruce ranged from 8 - 52% and averaged 33%, highest percent occurred at mid elevations w/some differences between aspects or soil types Branch and stem symptoms were abundant, unexceptional, and characteristic of well-appreciated red spruce symptoms Branch necrosis appeared associated w/crown abrasion caused by wind damage No significant symptoms were associated w/roots Seedlings were generally asymptomatic but not abundant **Red spruce show symptoms of moderate decline. Any role of air pollution was not clarified - full potential of survey will be realized if repeated in future**

continued

Table 7. Forest Condition Studies (continued)

SOURCE	STUDY MATERIAL & SITE CHARACTERISTICS	VARIABLES OF INTEREST	ASSOCIATED VARIABLES	RESULTS
Witter et al. EH03-2	Forest condition survey conducted in 3 plots at each of 5 sites in similar sugar maple-hardwood stands along a SO_4 deposition gradient from ne MN to sw MI	Tree species Mortality Biomass Recruitment (>5 cm dbh)	SO_4 deposition Relative location of site on gradient	Comparing the plot means of the 5 sites along the deposition gradient: no differences in net standing biomass or biomass increment of total stems or of sugar maple stems Differences in mortality were observed and are thought to reflect differences in drought conditions in 1988 Growth rates (biomass or basal area increment) of surviving trees (excluding newly recruited stems) at 1 site was higher than others **No conclusive evidence that SO_4 or NO_3 deposition is altering forest growth or mortality**
Zedaker et al. SF25-4 Nicholas et al. SF25-6 SF25-7	Four annual surveys of spruce-fir forests conducted in 129 plots, stratified by elevation, aspect and topography type Mt. Rogers, VA, Black Mtns., NC, and Great Smoky Mtns., TN and NC	Seedfall and viability Regeneration Crown condition Standing dead	Elevation (1524 - 1981 m) Location Time (1985-1989)	Basal area of standing dead trees increases with elevation Percent basal area of red spruce classed as dead: < 10% at all sites in Smoky Mtns., 2 lowest elevations in Black Mtns., and low elevation site at Mt. Rogers > 25% at highest elevation sites at Black Mtns. and Mt. Rogers Percent basal area of dead fraser fir ranged from 32 - 59% among Mt. ranges Red spruce crown condition declined over time and with increasing elevations in the Black & Great Smoky Mtns. from 1985-1988: no decline in crown condition at Mt. Rogers Germination of red spruce seeds within expected levels **No indication that abnormal events are occurring; no link to air pollution; droughts in 1986, '87, and '88 and an ice storm in winter of 1986 - 87 should be considered in evaluations of causes**

Table 8. Winter Injury Studies

SOURCE	STUDY MATERIAL & SITE CHARACTERISTICS	VARIABLES OF INTEREST	ASSOCIATED VARIABLES	RESULTS
Andersen & McLaughlin SF10-2	Red spruce saplings at 1720 and 1935 m elevation on Clingmans Dome, TN	Water relations assessed through analyses of pressure-volume curves on shoots	Elevation	During the period of cold hardening, saplings at higher elevation site had higher saturated osmotic potential reflecting lower solute concentrations **Low solute concentrations may reflect reduced winter hardening at the higher elevation site**
DeHayes et al. SF20-1	3-year-old potted red spruce seedlings, representative of Riversdale, and Chatham and Waterville Valley	Foliar N concentration Shoot growth Cold tolerance (electrolyte leaching)	Applications of NH_4, NO_3, with or without P fertilizer Timing of N application up to Level of N applied to rooting media (0, 300, 1500, 3000 kg N/ha/yr)	N supplements enhances cold tolerance ↑ foliar N concentrations associated with ↑ N treatment in all cases P had no effect on foliar N concentration or on cold tolerance Growth response to N supplements evident only for early-summer treatment Cold tolerance less responsive to nutrient supplementation applied in early summer period of active shoot elongation **Enhanced cold tolerance due to soil applications of N appears to be in direct conflict with "nitrogen fertilization" hypothesis**
Jacobson et al. SF06-3	Seedlings in field and lab. experiments Boyce Thompson Inst., NY	Cold tolerance of needles by electrolyte leakage	Sulfate and nitrate applications	**N fertilizer to roots lowered cold tolerance of needles prior to hardening, raised cold tolerance during hardening**
Sheppard et al. SF14-2	Sample shoots of red spruce from NY, TN, Scotland, Whiteface Mtn., and Newfound Gaps, collected at 1-3 weekly intervals	Autumn hardening assessed via development of visible tissue necrosis 14 days after freezing at various temperatures	Temperature records over past 22 years at the sites of sample collection	Historically, minimum air temperatures occasionally fell below the calculated LT_{10} (temp for 10% kill) Individual trees differed in hardiness by up to 10°C **Pollutant-induced freezing injury is insufficient, on its own, to account for red spruce decline in the Appalachians**
Wilkinson SF19-3	30-year-old red spruce trees in rangewide provenance test site planted in 1960. The 12 provenances range from 60-1620 m in elevation and from 35° 36' N to 46° 55' N	Annual radial growth 3-year radial growth 3-year height growth Basal area growth Crown injury/needle damage	Winter injury assessed annually for 3 years (1986-1988)	↓ in radial increment, basal area increment, and height were greatest for trees with the highest proportion of damaged needles in upper crown or those that were most frequently damaged over the last 3 years Radial growth reductions lasting up to 3 years was observed in trees injured in only a single year **Results support the hypothesis that winter injury is a contributing factor in red spruce decline**

See also the following studies:

Cape et al. SF14-4 Table 4, Eastern spruce and fir

Neighbour and Melhorn SF14-16 Table 4, Eastern spruce and fir

Fincher et al. SF16-4 Table 4, Eastern spruce and fir

Vann et al. SF34-2 Table 9

Table 9. Physiology Studies

SOURCE	STUDY MATERIAL & SITE CHARACTERISTICS	VARIABLES OF INTEREST	ASSOCIATED VARIABLES	RESULTS
Amundson et al. SP31-3	3 naturally regenerated stands of red spruce: Millinocket, ME - young stand, low elevation (518 m), low pollution Howland, ME - mature stand, low elevation (105 m), low pollution Whiteface Mtn., NY - mature stand, high elevation (1090 m), high acidic dep. and O_3	Net photosynthesis Foliar chemistry Stomatal Conductance	Age of stand Pollution level (confounded by elevation)	**Whiteface Mtn. vs. Howland** 1985: Ps > at Howland Stomatal conductance similar at both sites 1986 Ps and stomatal conductance similar at both sites 1987: Ps similar at both sites Stomatal conductance > at Howland 1988: Insufficient Data **Millinocket vs. Howland** 1985: Ps similar at both sites Stomatal conductance > at Millincoket 1986-87 Ps and stomatal conductance > at Millinocket 1988: Ps and stomatal conductance decline rate during autumn > at Howland **Whiteface vs. Maine sites:** **↓ Ps, foliar sugar, P, Ca and Mg** **↓ in foliar starch occurred one month earlier** **↑ foliar N** **Assimilation may be impaired, suggesting accelerated leaching from foliage or ↓ uptake from soil**
Halpin et al. SC18-2	Seedling and mature tree comparison of loblolly pine; Athens, GA	Needle retention Photosynthesis Stomatal conductance	Tree age (seedling vs. mature)	Seedlings vs. mature trees: 80% vs. 0% retention of previous year's foliage over winter 24% ↑ photosynthesis 24 % ↑ stomatal conductance ↑ number of flushes **Based on stomatal conductance, seedlings may be more sensitive than mature trees to air pollution**

continued

Table 9. Physiology Studies (continued)

SOURCE	STUDY MATERIAL & SITE CHARACTERISTICS	VARIABLES OF INTEREST	ASSOCIATED VARIABLES	RESULTS
Houpis et al. WC20-1	Mature ponderosa pine at 1280 m; Sierra Nevada Mountains, CA	$^{14}CO_2$ distribution within tree branches (branch autonomy)	Position of canopy branchlets pulsed with $^{14}CO_2$	**High degree of branch autonomy with respect to carbon allocation**
	Branch exposure chambers (BEC); Livermore, CA	Airflow & speed Air temperature Light intensity Ozone concentration CO_2 concentration Acidic precipitation deposition	Ambient vs. chamber environment Actual vs. target treatment concentrations	Air flow: > 3 chamber air exchanges/min., no dead spots, good mixing Air temp: < 3° C elevation from ambient Light: transmission of PAR > 90 % efficient Ozone: no sig. gradients (< 10 ppb differences w & w/o foliage); scrubbing efficiency > 80% CO_2: no sig. gradients (< 10 ppb differences w & w/o foliage); BEC can measure variation in CO_2 uptake due to natural ambient conditions Acidic depostion: rates vary from 12-19 mm/h **BEC performs well and meets performance requirements**
Kossuth SC11-1	Branches of mature slash pine grafted onto roots (mature clones) and rooted cuttings of juvenile spruce pine (P. glabra) (seedling clones) grown in greenhouse chambers	Diameter Height Branch length Stomatal openings (via electron microscopy)	4 levels of O_3 (0-300 ppb) for 1 year	High O_3 vs. 0 ppb: mature branches: ↓ 12% in diameter ↑ 8% in length ↓ 7% in height ↑ 80% size of stomatal openings in new needles reduced or altered wax layer over stomates seedlings: ↓ 78% total weight ↓ 45% height ↓ 43% diameter ↓ 88% root wight **O_3 reduces above ground growth and carbon allocation to roots; mature branches are similar (but less responsive) than seedlings; responses more pronounced on expanding tissue**
McLaughlin et al. SF10-3	30 saplings and 10 mature red spruce at 2 sites (1720 and 1935 m) in red spruce forests; Southern Appalachians, NC	Net Ps and dark respiration Plant and soil chemistry Growth	Elevation Light levels	Greater radial growth decline at higher elevation over last 20 years Greater radial growth decline at lower elevation during last 5 years High elevation vs. lower elevation: sapling growth 40% slower ↓ Ps at low light level, no difference at saturated light level ↑ Respiration foliar nutrients: ↑ Al; ↓ Ca, Mg, P; similar N soil concentration: ↑ P, K, Al; ↓ Ca ↑ **atmospheric inputs of anions at high site may mobilize Al in soil and in tissue adversely affecting physiology**

continued

Table 9. Physiology Studies (continued)

SOURCE	STUDY MATERIAL & SITE CHARACTERISTICS	VARIABLES OF INTEREST	ASSOCIATED VARIABLES	Results
Norby et al. SF10-1	Red spruce seedlings/saplings from 3 sources grown in green house: New Hampshire and Nova Scotia, both 1 year old (from nursery); Great Smoky Mtn. N.P., 5-15 years old.	Nitrate reductase activity in needles Visible injury	Exposure to simulated: NO_2 (75ppb) HNO_3 (75ppb) Acid mist (pH 3.5 and 5.0) Plant source	NO_2 induced nitrate reductase in both nursery-grown seedlings and older saplings from the GSMNP though nitrate reductase activity was lower in nursery-grown seedlings HNO_3 vapor also induced nitrate reductase activity Acid mist containing nitrate did not induce nitrate reductase activity No visible foliar injury with NO_2 exposure Significant visible injury with HNO_3 exposure No nitrate accumulation in needle tissue for both HNO_3 and NO_2 exposures **Red spruce is capable of assimilating NO_2 and HNO_3 vapor, therefore excess N hypothesis is tenable**
Rebbeck et al. SF32-1	Experiment I: Red spruce juvenile (< 4 years) and mature (> 25 years) scions grafted on rootstock in open-top chambers at low-elevation sites in Maine Experiment II: Red spruce and balsam fir seedlings grown in open top chambers as above with different O_3 regime	Exp I: Diameter, height Net photosynthesis Stomatal conductance Chlorophyll content Exp II: Diameter, height Net photosynthesis Stomatal conductance Chlorophyll content	Experiment I: 5 levels of O_3 (CF-ambient + 150 ppb) 4-5 mo/yr for 2 years Experiment II: 3 levels of O_3 (AA, CF, & NF) Yr1 - 2 months Yr2 - 4 months 2 mo/yr for 2 years	Experiment I: At highest O_3 (ambient + 150 ppb) juvenile scion diameter growth ↓ 27%. No other treatments were significantly different from CF air for either juvenile or mature scions 23% ↑ chlorophyll content in juvenile rootstocks vs. mature or juvenile scions. Chlorophyll content of mature needles > juvenile needles Highest chlorophyll levels at ambient + 75 ppb At ambient + 150 ppb, photosynthesis was reduced by 44% & 29% for juvenile and mature scions, respectively Experiment II: Chlorophyll content of balsam fir > red spruce Highest levels of chlorophyll occurred at CF for both spp. No growth data available
Vann et al. SF34-2	Branch chambers on each of 4 mature red spruce for 3 months at 1160 m; Whiteface Mtn., NY	Needle: mass chlorophyll carotenoids cuticle thickness total-cutinized layer thickness Stomatal wax plugs Winter injury	Removal of: cloud mists O_3 (and other charcoal-reactive gases) Addition of "clean" mist	Photosynthetic pigments, cuticle, wax: ↑ w/removal of "pollutants" and addition of "clean" mist no change w/removal of "pollutants" only No treatment effects on needle mass Winter injury: ↓ w/removal of "pollutants" and addition of "clean" mist **Ambient cloud mists and O_3 affects foliage and increases winter injury. Interaction observed with humidity**
Wiselogel SC18-3	14-year-old loblolly pine growing in a plantation Athens, GA	Leaf area Net carbon exchange Dark respiration Branch growth	O_3 (ambient to ambient) Water availability (Irrigated vs. non-irrigated)	↓ photosynthesis in 2.5x ambient treatment **Response of 14-year-old trees is similiar to response of seedlings**

Table 10. Insect/Pathogen Studies

SOURCE	STUDY MATERIAL & SITE CHARACTERISTICS	VARIABLES OF INTEREST	ASSOCIATED VARIABLES	RESULTS
Bruck SF02-3	Survey of insects and pathogens in spruce-fir forests, 1985-1988; Southern Appalachians	Insect/pathogen presence: stems branches foliage roots	Tree decline	No correlation between tree decline and insects except balsam woolly adelgid Balsam woolly adelgid was found on 50% of fraser fir **Biotic insect and pathogen infestation not important in red spruce decline in southern Appalachians**
Grehan SF99-16	I: Larvae and adults of conifer swift moth surveyed in spruce-fir forests on Mt. Moosilauke and Whiteface Mtn. between 500-1300 m II: One year old red spruce seedlings inoculated with larvae in field at Mt. Mansfield and Whiteface Mtn.	I: Larval density II: Foliar dieback Root mass	I: Aspect Elevation II: Larval presence	I: Larve and adults were recorded at all elevations and abundant at 700 - 1100 m Greater larval numbers occur on slopes facing prevailing winds II: Presence of one or more larvae per seedling resulted in significant increases in foliage dieback and reduced root mass **Conifer swift moth Korscheltellus gracibis is common in the NE and potentially a factor affecting red spruce regeneration**
Hartman et al. SF02-4	Fraser fir and red spruce trees at varying elevations; Southern Appalachians	Parasitic nematode densities Composite soil-root samples Tree decline status	Elevation	With ↑ elevation: ↑ plant-parasitic nematodes, tree & crown decline Weaker or negative correlation of nematode densities with crown decline **Nematodes probably not related to crown condition**
Knight & Grosman SF99-6	Spruce-fir forests; 3 plots (750, 960, & 1110 m) at Mt. Moosilauke, NH; 2 plots at Howland, ME	Insects Other invertebrates	Elevation	33 insect species associated with red spruce and/or balsam fir were found Large numbers of ghost moth (may contribute to red spruce decline) **No indications of epidemics or outbreaks associated with tree decline**
Smith & Armstrong-Collaccino SF05-12	Pathogenic symptoms visually assessed on 189 co-dominant red spruce trees in 19 plots at stratified locations Mt. Moosilauke, ME	Roots: fungal/insect infections Forest floor: nematode densities	Elevation (824-1172m) Aspect (e & w) Soil type (histosols vs. spodosols)	No relationships to elevation, aspect, or soil type were observed No significant infections or physical wounds were observed on fine roots Forest floor nematodes exhibited high population densities (by Bierman Funnel technique) between 20,000-50,000 worms/100g(dw). Nematodes pathogenic to red spruce roots were not specifically determined.
Tobi et al. SF99-7	Spruce-fir forests; Camels Hump Mtn., VT	Ghost moth densities	Elevation	Larvae, pupae, and adults present at all elevations, with more present at higher elevation, (positive correlation) Large number of dead seedlings exhibited girdling injury **Moth larvae are agents of seedling mortality**
Weidensaul et al. SF08-6	High-elevation spruce-fir forests; Whiteface Mtn., NY	Insect/pathogen presence	Elevation Crown class Tree dbh Species	**Insects and facultative parasites are not important as triggering stresses in the process of tree decline**

Table 11. FRP Literature Review

SOURCE	TOPIC OF REVIEW	CONCLUSIONS
Air Pollution and Winter Injury of Red Spruce Workshop Results (Adams, ed.)	Summary of results from working groups on a) cold tolerance and winter injury under ambient conditions b) experimental results c) physiological/biochemical mechanisms	Current-year needles of red spruce are inherently susceptible to winter injury because of low mid-winter hardiness levels and because of the likelihood of mid-winter dehardening during above-freezing temperatures Lab studies show that sulfate, but not nitrate, deposition can reduce fall and early winter cold tolerance of red spruce by 3-4°C, thus increasing susceptibility to winter injury The cause of winter injury symptoms in the field has yet to be elucidated because "critical" temperatures for the field cannot be determined from lab studies, and examination of current data on field winter injury and weather conditions does not clearly suggest either desiccation or freezing **The hypothesis that air pollution predisposes high-elevation red spruce to winter injury via reduced cold tolerance is tenable but natural mechanisms, especially winter injury via environmentally induced desiccation, cannot be ruled out as an explanation of increased winter injury. While there is evidence of forest decline as a result of localized severe winter injury, this relationship is not well established because winter injury does not occur consistently with severe climatic conditions**
Binkley et al. SC16-2	Evaluate susceptibility of forest soils to chemical changes due to S & N deposition in SE US	Leaching losses of base cations may have ↑ in an amount equal to about 0.5 to 1.0 kmol/ha/yr as a result of acidic deposition, perhaps representing a doubling or tripling of background rates Cannot assume weathering rates are sufficient to prevent depletion of exchangeable cations **Does not support the assumption that forest soils in the South will remain relatively unaffected by the deposition of S & N compounds**
Cline et al. SC09-1	Effects of N on mycorrhizae in SE US and world-wide	**No direct adverse effects of deposited N on mycorrhizae expected**
Cregg et al. SC18-1	A literature review highlighting ecophysiology differences of seedling and trees as a consideration when evaluating responses to environmental stimuli	At the level of physiological processes, seedlings and trees often perform alike. Great differences exist in structure and form which may lead to significant differences in diurnal and environmental responses
Flagler et al. Southern Case Study SC99-20	The research strategy of the Southern Commercial Forest Research Cooperative and its most current findings (9/89) with regard to forest decline. Emphasis is on results of controlled exposures of O_3 and acidity to southern pine seedlings in screening studies (1st yr), at Intensive Research Sites (2nd & 3rd yr), and from mature branch studies. Conclusions predicated on incomplete results from all studies; conclusions may change as these studies or additional analyses are completed	Acid rain: No evidence of negative effects upon the growth and physiology of southern pines (based upon studies designed to study short-term, direct foliar effects, rather than soil mediated effects) Ozone: Convincing evidence of significant negative effects on the growth and physiology of southern pines: ↓ Ps, ↓ chlorophyll, and altered carbon and nutrient status. Results varied significantly due to genotype, but combined analysis of 21 genotypes was negative overall Ambient concentrations impaired growth and physiology in many instances, but in other instances effects were not noted until 2 x ambient or at any concentration ; in one case, growth increases were observed at 1.5 x ambient O_3 Many growth effects manifested after the first year of exposure may be linked to a premature senescence of foliage associated with O_3 Seedlings and mature trees were both affected negatively, but seedlings appear more susceptible Acid rain x ozone: Few interactions noted; where present ↓ pH resulted in more negative ozone effect

continued

Table 11. FRP Literature Review (continued)

SOURCE	TOPIC OF REVIEW	CONCLUSIONS
Garner et al. SC01-1	Literature review to determine which substances are most likely to affect eastern hardwoods, spruce-fir, and southern pine forests: 1) O_3 and other photochemical oxidants, alone, or in combination with acid deposition or 2) atmospheric deposition of acidic and acidifying substances alone Review concentrates upon above-ground, foliage-mediated responses and contain no FRP results	Ambient deposition of S and N probably will increase growth in many eastern forests; detrimental effects of N deposition are more likely in high-elevation forests O_3 has been proven to cause foliar injury and decrease growth in some eastern white pine seedlings and also induce visible foliar injury and decreased photosynthesis in several species of pine and oak seedlings. Ambient O_3 concentrations in eastern North America are sufficient to decrease photosynthesis and growth, increase foliar injury, and alter C allocation between roots and shoots in sensitive and intermediately sensitive vegetation SO_2 can reduce photosynthesis and growth, increase foliar injury and mortality, and alter C allocation between roots and shoots. SO_2 concentrations in areas near major point sources cause visible injury to vegetation, but concentrations are rarely high enough to be injurious to forests at the regional level Gaseous NO_x at ambient concentrations not proven to cause increased foliar injury, increased mortality or decreased growth of trees The co-occurrence of phytotoxic concentrations of O_3, SO_2 and NO_x are rare, thus eastern US forests appear to be at low risk of injury from gaseous pollutant mixtures (based on present but inconclusive evidence) **Toxic gases are the only airborne pollutants shown to cause visible injury, decreased growth, and mortality of forest trees in North America. Acid deposition at ambient concentrations has not been shown to induce detrimental effects on forests**
McLaughlin SF10-13	Summary of key C assimilation and allocation processes; summarizes gaps in understanding of pollutant effects on these pathways	Information need: Quantification of interrelationships between photosynthesis, respiration, translocation, and metabolic repair as they influence availability of photosynthate under chronic exposure to pollutants Characterization of shifts in C allocation between roots and shoots due to direct and indirect effects of pollutants and deposition Evaluation of changes in levels and types of storage reserves in pollution-stressed trees, in terms of altered resistance to disease and altered physiological resilience Examination of time series of growth patterns of larger trees in the field to test for shifts in response to natural stresses
Meadows et al. SC03-1	Natural and airborne chemical stresses on growth of trees and forests	Direct effects of simulated acid precipitation on trees have been demonstrated, but only by treatment with artificial acid precipitation of pH 3.0 or less Indirect effects of acid precipitation on forest productivity may occur through alterations in forest soils Field studies have thus far failed to demonstrate that these potential effects have occurred over a widespread area in North America No conclusive evidence that acid precipitation has caused detrimental effects on forest productivity in North America Short-term exposures to high concentrations of gaseous pollutants are more detrimental to photosynthesis and growth than long-term exposures to low concentrations at equal doses Ambient O_3 concentrations above 50 ppb have been shown to cause reductions in net photosynthesis and growth of several types of vegetation, even in the absence of visible injury O_3 (and possibly other oxidants) is the only regionally dispersed air pollutant known to have injured foliage, decreased growth, and increased mortality of sensitive tree species over a wide geographic range Heavy metals deposited from the atmosphere or mobilized in soils are important, at least on a local scale The diversity of sites, species, and stand conditions exhibiting decline argue against any one single factor as the primary causal agent in the observed declines in Europe and the Northeast Natural stresses, especially drought and temperature stress, may be much more detrimental to vegetation than airborne chemical stresses

continued

Table 11. FRP Literature Review (continued)

SOURCE	TOPIC OF REVIEW	CONCLUSIONS
Miller et al. EH02-1	Tree mortality events in the eastern hardwoods over the last century were reviewed to determine whether, there are relationships between mortality patterns over time and current patterns of atmospheric deposition. Species considered were: American beech, black cherry, eastern white pine, northern red oak, shagbark hickory, sugar maple, white oak, yellow birch, and yellow-poplar.	The apparent increase in the decline and mortality of many hardwood species during the last few decades may be due to intensification of reporting and to maturation of the forest itself Most mortality is due to abiotic and biotic stress factors such as weather, silviculture, and damage by insects and disease There is evidence of damage to hardwoods by atmospheric pollutants from point sources such as smelters, and to eastern whitepine from ozone **There is no conclusive evidence of an association between patterns of hardwood mortality and regional atmospheric pollution**
Richter Southern Case Study SC99-19	Effects of S & N deposition on forest soils of the SE US	Two important soil-mediated effects are likely due to acidic S & N deposition: 1) negative short-term effects of accelerated leaching of Ca, Mg, & Al due to SO$_4$ deposition 2) positive long-term effects of N fertilization on forest productivity, the timing and magnitude of which are uncertain because of lack of information on rates on N transformations and of the contrasting influence of intensive forest management Forest soils most susceptible to these effects have moderate to extreme acidity, low CEC, and low weathering rates Areal extent of forest soils susceptible to these effects has been estimated at 2.8-15.9 mil ha (based upon data with large uncertainties Processes countering acidification and leaching in highly weathered soils: 1) soil sulfate absorption 2) nutrient cation uptake by deep roots 3) release of nutrients from secondary soil minerals 4) atmospheric deposition of nutrient cations **Acid deposition is expected to affect soils; timing is unknown**
Shadwick et al. Southern Case Study SC99-21	Ambient air monitoring of wet and dry deposition (1978-86) and gas concentration (1978-83) for 6 regions in the south: 1) Piedmont 2) Inner Atlantic Plain 3) Eastern Gulf Plains 4) Western Gulf Plains 5) Outer Atlantic Plain 6) Eastern Gulf Flats	Range for 6 regions: pH: 4.47 - 4.81 SO$_4$: 0.95 - 1.88 mg/L; 12.00 - 21.35kg/ha/yr NO$_3$: 0.60 - 1.00 mg/L; 7.00 - 11.60kg/ha/yr NH$_4$: 0.07 - 0.22 mg/L; 0.63 - 2.38kg/ha/yr O$_3$: 7-hour mean = 51 ppb in Piedmont/mountain/ridge regions, 43 ppb in coastal plain region SO2 & NOx rarely at harmful concentrations long enough to injure plants **Annual precipitation-weighted concentration and wet deposition levels for H, SO$_4$, and NO$_3$ ions are significantly higher in the Piedmont than each of the other regions**